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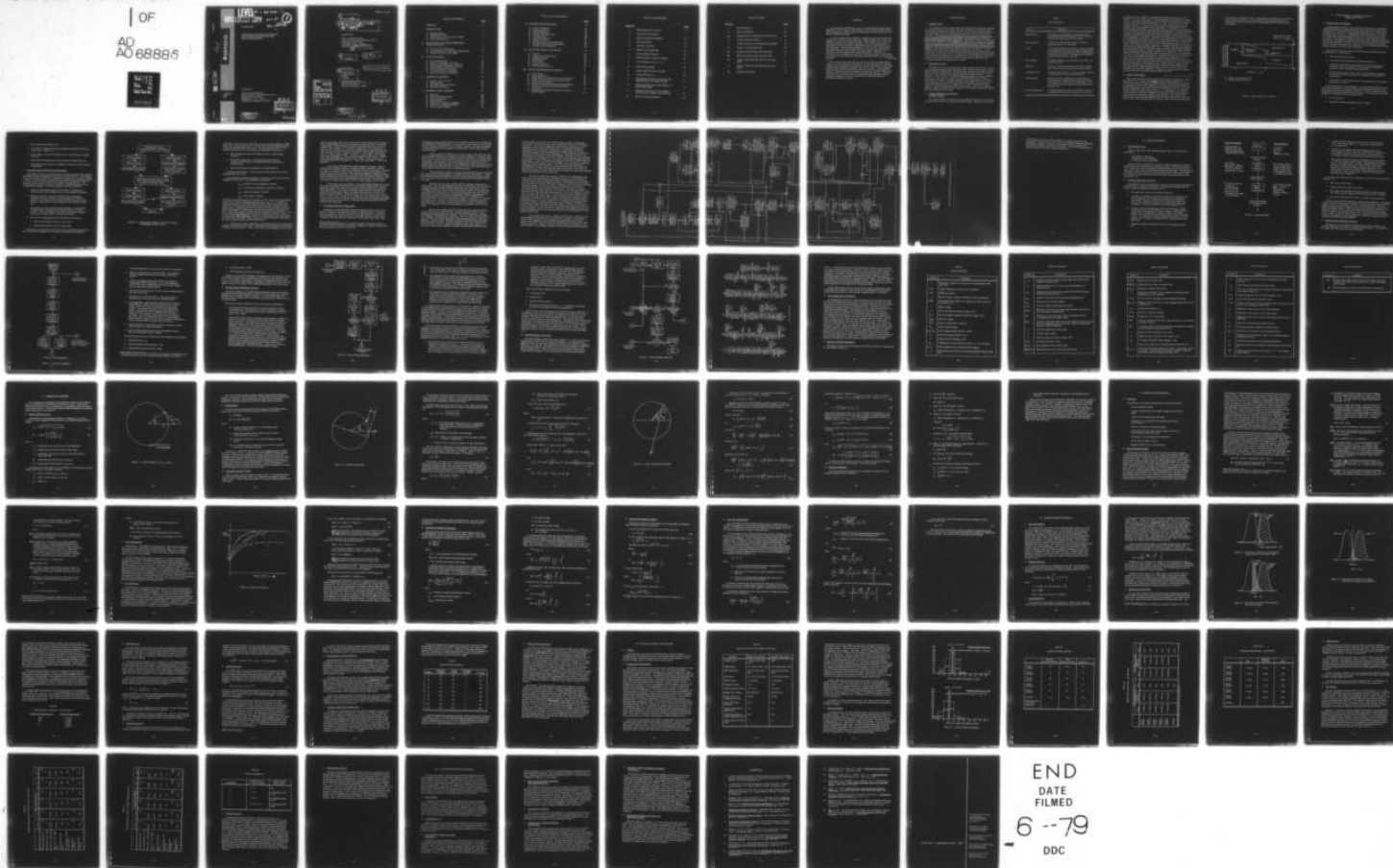
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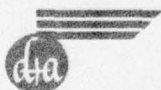
DESCRIPTION AND STATUS OF SEARCH
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SQS-23 (TRAM) SONAR

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Prepared for:

Chief of Naval Personnel
Bureau of Naval Personnel (Pers-C133)
Department of the Navy
Washington, D. C. 20370
Contract No. N00022-67-C-0172

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⑨ Interim Report

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ABSTRACT

A sonar search and detection model is being developed under contract N00022-67-C-0172, Item 2. The primary concern of this contract item is the development of a Sonar Operator Performance Standards Guide for the SQS-23 TRAM Series Sonar.

To develop performance standards, models which represent different aspects (e. g., detection, long- and short-range tracking, etc.) of the sonar operator's activities are being developed. Concurrently, the models are being implemented as computer programs which can be exercised and analyzed more easily and more exhaustively than the real world activities they represent. Using model manipulation, it is practical to determine optimal performance under wider variety and larger combination of circumstances than would be feasible with field studies. Whereas, no provision for field validation is made in the present contract, every effort is being made to keep the model consistent with performance data currently available. *what data*

→ This interim report describes the search and detection performance model in its current state of development. It also describes the computer program which implements the model and some of the tentative conclusions resulting from running the program in its current state. The conceptual model includes many pertinent characteristics of the sonar hardware, its operator, and the acoustic environment in which they operate. Additional characteristics will be included in an extended model and implementing computer program to provide a sound basis for the Sonar Operator Performance Standards Guide. ↗

I. INTRODUCTION

A. Program Goals

The purpose of the task under which this interim report has been prepared is to provide the Navy with a Sonar Operator Performance Standards Guide for the SQS-23 TRAM Series Sonar for use by sonar operators and supervisors, destroyer ASW officers and commanding officers and fleet training activity personnel. The progress reported herein concerns specifically the development of detection performance standards for representative environmental conditions and equipment operating modes. The method chosen for the development of these standards is the synthesis and exercise of a computer simulation model which faithfully represents the interaction of the sonar system with the ocean environment, and the sonar operator with the sonar system displays and controls. This simulation must reflect both the sonar system in its current configuration and the body of procedures and doctrine for its use. It must account for the effects of the tactical situations and ocean environmental conditions which actually exist at sea. It must reflect the psychophysical limitations of the operator, his behavioral predispositions, and the logic processes used by him in the detection process. And it must be based on the best of the procedures and doctrine imposed by or on him.

B. Definition of Terms

Development of the simulation model, then, requires work in the areas of experimental psychology, signal detection theory and decision theory, systems analysis and naval operations. One quickly notes the fact that identical words and phrases have separate and distinct meanings in different areas. As an example, "False Alarm" to the experimental psychologist, means a response where there is no stimulus, while to the decision theoretician it means a response where there is a stimulus present but no target (noise), and to the naval officer it means a response (detection) where there may or may not be a target present but there is no submarine. To clarify discussion in this report, the definitions shown in Table I will be used. There is no attempt implied to gain acceptance of these definitions for purposes beyond the reading and understanding of this report.

C. The Sonar Operator's Function in an ASW Encounter

The sonar operator's functions during an ASW encounter can be described by three words; detection, classification and tracking. Detection answers the

Table I

Basic definitions

Term	Definition
Sonar Search	The process of surveillance of the body of water surrounding a ship to determine if there is a sonar reflector present, and if so, its location.
Sonar Contact	A return or stimulus from a sonar reflector or target located in or on the water.
Alarm	A stimulus-induced sensory event causing a response by the operator which results in some modification to the ordered or self-imposed video scanning pattern or audio search pattern. An alarm affects only the performance of the sonar operator.
False Alarm	A response which occurs when there is, in fact, no stimulus present.
Detection	An event. The decision and report by the operator that a sonar contact is present at a given location.
False Detection	A detection when there is, in fact, no sonar reflector or target present at the reported location.
Classification	Given an alarm, classification is the process of determining the probabilities that the sonar contact is a submarine or that it is not a submarine. It is also the decision and report reached on the basis of this process.
False Classification	A detection and report that a given sonar contact is a submarine when, in fact, it is not or vice versa.

question "Is there a target?", classification answers the question "Is it a submarine or a non-submarine?", and tracking answers the question "Where is it?". Tracking as performed by the fire control system and its operators answers the question "Where will it be?", but this is not directly a sonar operator function. He contributes with his present position data and with ancillary data such as doppler and aspect angle. We sometimes like to consider these three phases as occurring in series, with Detection occurring first, Classification next, and finally the Tracking phase. In actual operations, all three occur simultaneously from perception until a detection decision is reached, and after that classification and tracking both continue until the end of the engagement or incident. It should be noted that while the detection phase is terminated by a detection decision, the classification phase is not terminated by a classification decision. Since the classification decision is probabilistic rather than definitive (except in the case of overpowering evidence such as a sonar contact firing a torpedo), it must be continuously updated on the basis of the information supplied by the latest echo. A useful concept is that detection and classification form a continuum and that the shift from the detection phase to the classification phase is one of emphasis or orientation. Thus, strong submarine-like echo classification characteristics noted prior to the detection decision will encourage rapid detection. And detection, in itself, forms the first level of classification in which a determination, based on the echo characteristics and the probabilities involved, is made that the source of a given echo is a sonar reflector in the water rather than noise or reverberation. One of the possible if not probable causes of short detection ranges is that operators are waiting to make the detection report until the classification process indicates a high probability that the contact is not merely a sonar reflector but is in fact a submarine. Figure 1 is a graphical presentation of the sonar operator's activities during an ASW encounter.

D. Scope of This Report

Computer program completed?

This report will deal with the detection function as outlined above. More specifically, it will report on the status of the computer program for the simulation model of the detection process which is being prepared to provide the statistical basis for the formulation of operator performance standards. A substantial portion of the work done has already been reported in previous formal submissions under this contract.^{1, 2, 3} Where this is so, such work will be referred to rather than recopied for this submission. The larger portion of the work thus far completed has been involved with the operator's visual activities rather than with his aural activities. As a result, this report will be more heavily weighted in that direction than will the final simulation model. Where appropriate, on-going or future work will be described

in conceptual or qualitative terms. The program descriptions will include the actual computer program as it now stands and will be distinguished from formulated concepts in the process of being debugged and incorporated into the program.

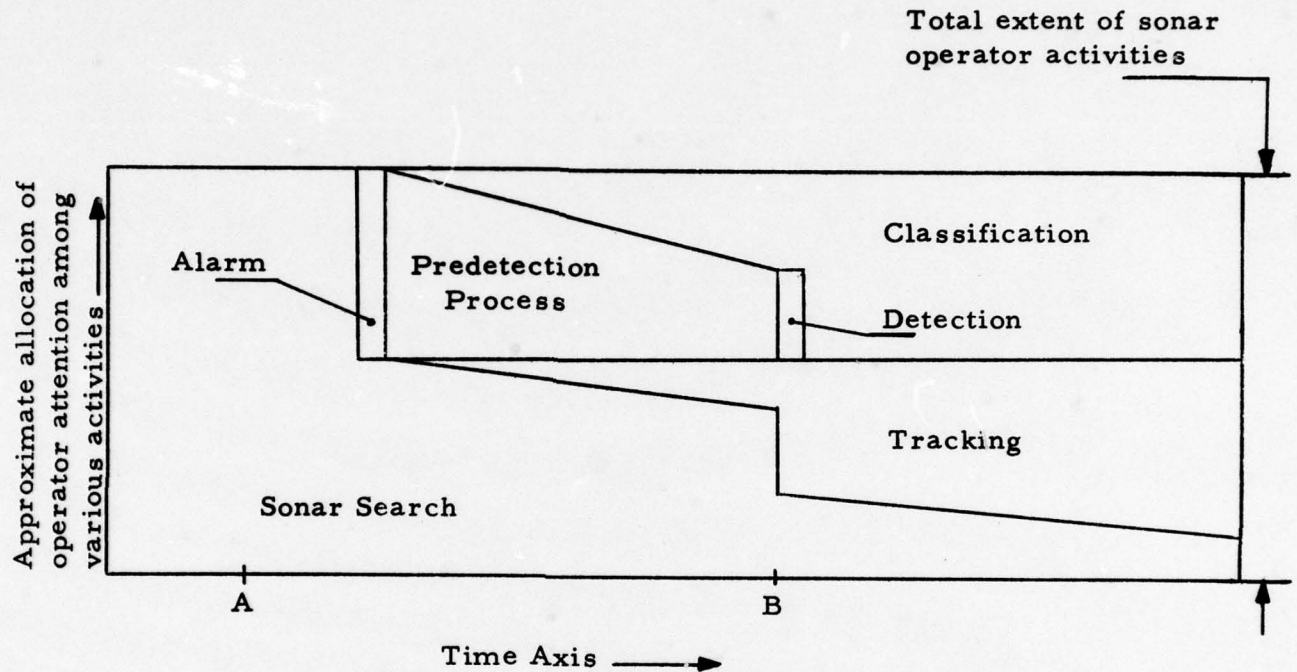


Figure 1. Sonar Operator's Activities

II. DEVELOPMENT OF SONAR OPERATOR DETECTION LOGIC

A. Need For Such Development

In studying the process of sonar search with the objective of somehow establishing methods of measuring operator performance and establishing standards for such performance, one soon comes face to face with certain inconsistencies. There is a considerable body of analytical search theory and signal detection theory, a growing field of decision theory, and there are considerable experimental data in the area of psychophysical sensory perception. When these are combined with sonar system physical parameters and the sonar propagation properties of the oceans, they can yield a prediction of system performance in search. However, these predictions have been found to be highly optimistic when compared to actual detection performance in fleet exercises or in less formal exercises.

This difference between predicted and actual search performance has been attributed to a summation of:

1. Poor equipment maintenance.
2. Less than optimum equipment operating adjustments.
3. Command involvement in other than ASW mission assignments along with a lack of appropriate overall penalties for ineffectiveness in ASW during peacetime operations.
4. Overriding variation in actual water sound propagation conditions encountered from those assumed in computation of the predicted performance.
5. Artificialities in the measurement of the psychophysical perception parameters involved.

However valid these factors might be, it is also possible that they mask some basic differences in concept between the processes analyzed for prediction and the processes measured in the fleet. It was in pursuance of this thought that a detailed examination of the process of sonar search at sea was conducted. The basis for this examination was:

1. Tactical doctrine.
2. The sensory and psychophysical factors involved.

3. Sonar equipment design factors.
4. The impact of underwater sonar propagation phenomena (reverberation, noise, fading, etc.)
5. Search theory, statistical decision theory, and the theory of signal detection.
6. Discussion with experienced sonar operators and ASW officers.
7. Discussions with scientific investigators in the area of sonar search and detection.

B. Conceptual Basis For The Logic Development

The method selected for this examination was the preparation of a detailed Operational Sequence Diagram for the process of sonar search. This diagram will show the logic flow used by the operator during search, during his response to audio or visual stimulus, and during the correlation and processing phases which occur prior to his decision that a contact has been detected. The Functional Flow Diagram, Figure 2, provides a simplified summary of the results of this analysis. The initial conditions used are as follows:

1. Operator using ordered audio search pattern. Designation of such a pattern at the command level is currently part of doctrine.
2. Operator using the ordered or standard video scan pattern. Designation of such a pattern is currently not part of doctrine. However, each operator must develop some self-imposed routine pattern to insure that he will methodically cover the entire scope face.
3. The operator is using the Ship Centered Display, the Sum Mode, a medium pulse, with gain and intensity settings according to doctrine. The search logic is not affected by periodic changes in range scale or pulse length if required by doctrine.
4. The operator using designated or self-imposed criteria for:
 - a. Initial video detection event or video alarm.
 - b. Initial audio detection event or audio alarm.

These alarm or perception criteria are not now designated by doctrine, and it is difficult to imagine how they might meaningfully be specified or

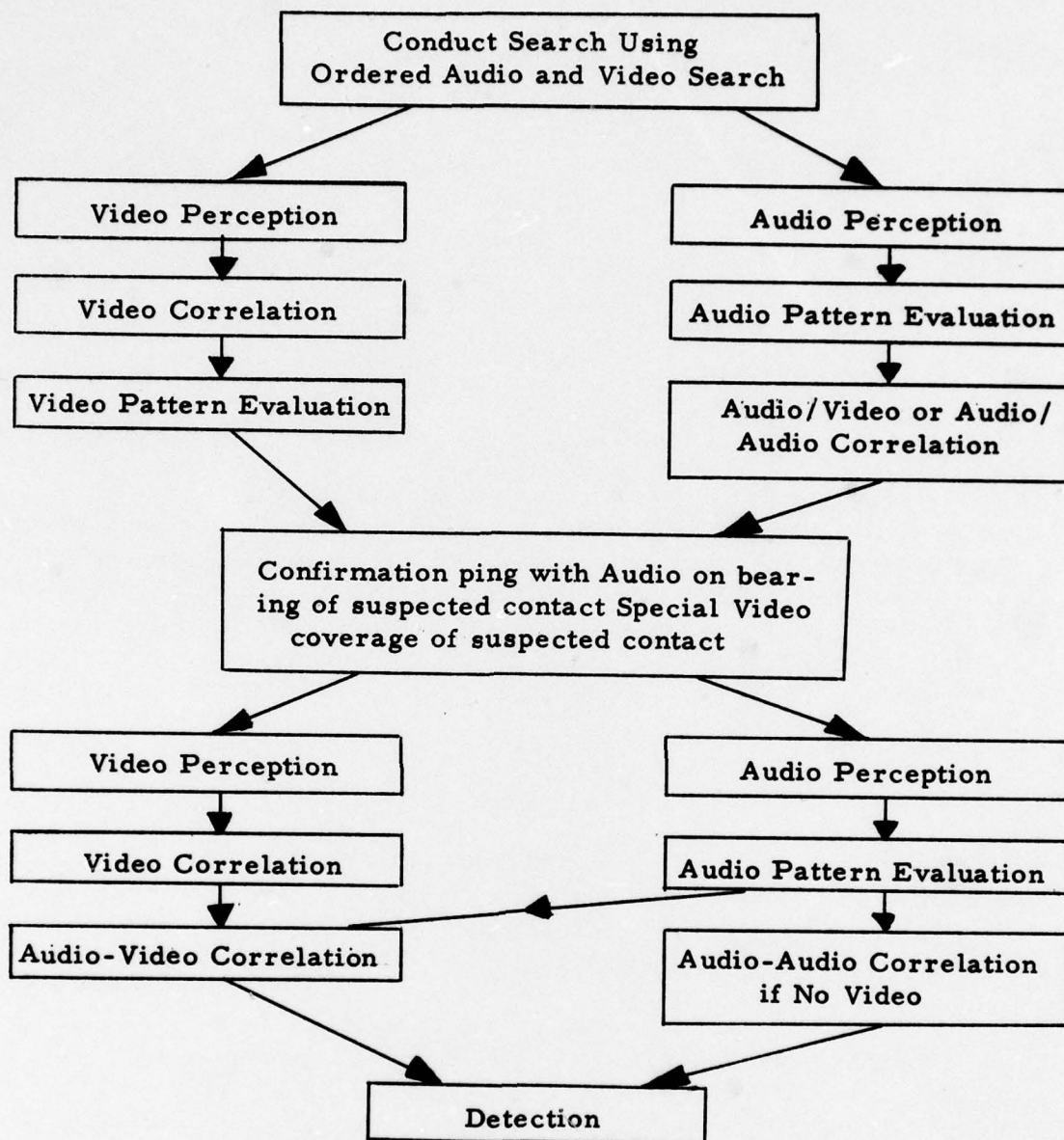


Figure 2. Functional flow diagram of operator activities during SQS-23 sonar search.

controlled. Decision theory would base such a criterion designation on false alarm rate, but how can one set a criterion under specific conditions which will give a specified false alarm rate? The self-imposed alarm criteria used by the operator are in fact empirical summations on his part of:

- a. His training and relative proficiency in video or audio signal detection.
- b. His previous experience, involving previously achieved detections, false alarms, and false detections using various criteria levels.
- c. The tactical mission and situation as he understands it.

It should be noted that it is only in the last of these factors that direct command input can be felt.

In the Operational Sequence Diagram, the alarm criterion levels will be designated by the letter T with appropriate subscripts.

T_{pv} = peripheral vision brightness criterion

T_{fv} = foveal vision brightness or definition criterion

T_{ai} = audio echo intensity criterion

T_{ad} = audio doppler criterion

The level of the signal observed in relation to these criteria will be designated by the letter I with corresponding subscripts (I_{pv} , I_{ad} , etc.). It should be noted that the alarm criteria discussed here refer only to a decision by the operator to interrupt his normal search routine in order to examine a given signal return. These alarm criteria are those normally measured and evaluated in psychophysical experiments, used in detection theory and decision theory, and used in analytic system detection performances predictions. They are among the necessary criteria to be met in making a decision, but they are not, taken singly, sufficient conditions for determining in the fleet whether a detection has been made. Hence, they are not the only factors which must be used in predicting fleet detection performance.

5. The operator using a designated or self-imposed criterion for determining when a detection has been made. Designation of this detection criterion has not been a part of doctrine. The fact that such a criterion does in fact exist and

that it is not simply one or more of the alarm criteria discussed in the paragraph 4 above became obvious when speaking to sonar operators. One finds considerable variation between operators concerning the relative utility of audio or video, doppler or echo quality, brightness or size in detection. Whatever their preferences, given the situation that the signal has exceeded their criterion you ask, "Would you report it?" The answer was always, "Oh, no. Not on just one ping." "On two?" "Well, maybe. But it would have to be awfully good." "Even if you got both audio and video?" "Maybe, but you would probably want a third look, at least. There would be too many false detections with just two." "Well, how many then?" "Well, that depends...."

The nature of the detection criterion begins to emerge. It has to do with ping-to-ping correlation, and audio-visual correlation of stimuli. It is such a correlation criterion on which this analysis is developed. Because of fading, the criterion cannot require stimuli on successive pings and two pings are generally insufficient. The Operational Sequence Diagram prepared in this analysis used a basic three ping out of four correlation criterion. Such selection was based on the minimum that was considered to be realistically achievable and operationally valid; however, other criteria could be used.

L such as?

Such ping-to-ping correlation, with the associated probabilities, must be used in any analytical prediction of fleet detection performance, and any meaningful simulation of the search process must include such correlation.* More importantly, it provides a convenient means by which command can, indirectly but effectively, specify acceptable false detection rates for the tactical situation existing. Three out of four, two out of three, three out of three, two out of four, six out of ten, and fifteen out of twenty ping correlation criteria would all lead to different false detection rates and different time lags between first alarm and detection. And they would have meaning to both the bridge and the sonarman.

C. The Detailed Detection Logic Model

Looking now at the Operational Sequence Diagram, Figure 3, the first general comment is that the video channel is represented on the left-hand side of the diagram, the audio channel on the right-hand side. A detection range advantage is normally attributed to the audio channel, but the sector coverage of the audio search is only about 10^0 per ping, while video sector

*Recent informal discussions with analysts from the Operations Research Division at the Naval Weapons Laboratory, Dahlgren, Virginia, indicate that they have arrived at similar conclusions.

coverage per ping is essentially 360° on the TRAM versions of the AN/SQS-23. The likelihood of initial detection by video means is much greater than by audio means because of this difference in coverage. However, the range advantage for audio detection will be important in formulation of some of the decision rules used later.

Another result of the difference in sector width on the audio and video presentations is that audio correlation of a video response is not likely on one ping, but video correlation of an audio response is possible, and perhaps likely, on one ping. The only way to effectively test for audio-visual correlation on a given ping is to interrupt the audio search pattern by training the cursor to the bearing of the suspected contact, and modifying the video scan pattern to the extent required to insure special coverage of the area of the suspected target. This is done on what can be called a confirmation ping.

True? | The next thing to consider is what is sufficient justification to interrupt the ordered audio search pattern or to modify the video scan pattern. It must be assumed that the ordered audio and video search patterns provide optimum area coverage, and any departure therefrom represents a degradation in this coverage.

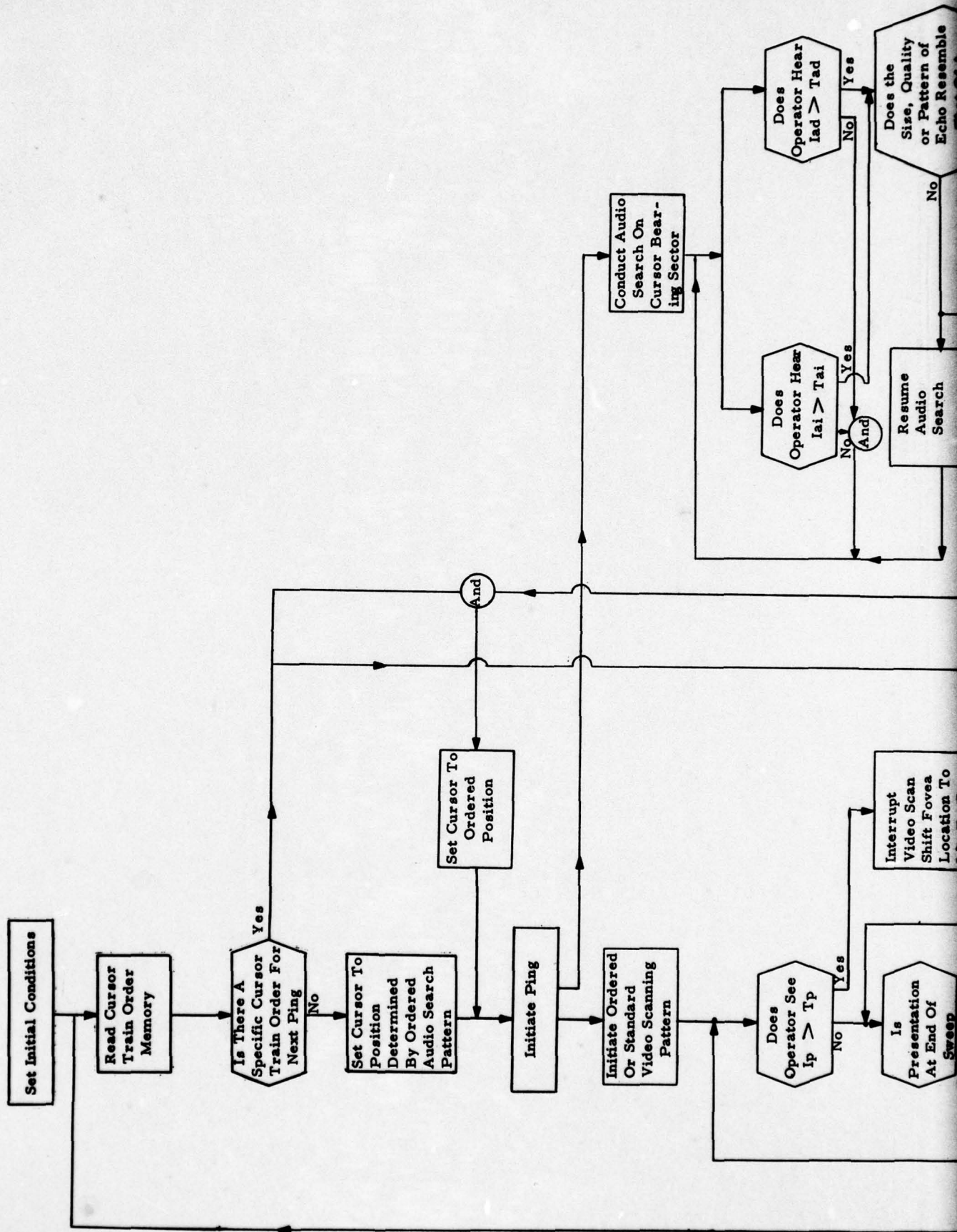
Consider first the video channel, with the operator conducting his visual scan. If he sees a bright area any place in his field of vision (a function of target brightness, angular displacement from the fixation point, and the probabilities involved: see reference 1), his gaze will shift to the bright area as a subcortical reflex action. If he then sees the bright area with his fovea (a function of eye movement time and phosphor brightness degradation), he determines whether its location correlates with that of a peripheral or foveal detection event on one of the last two pings. If it does not, he continues his ordered scan. If it does, he determines whether it exhibits target-like characteristics. If it does, he enters the order to conduct a confirmation ping on that bearing for the next transmission and continues his scan for the ping.

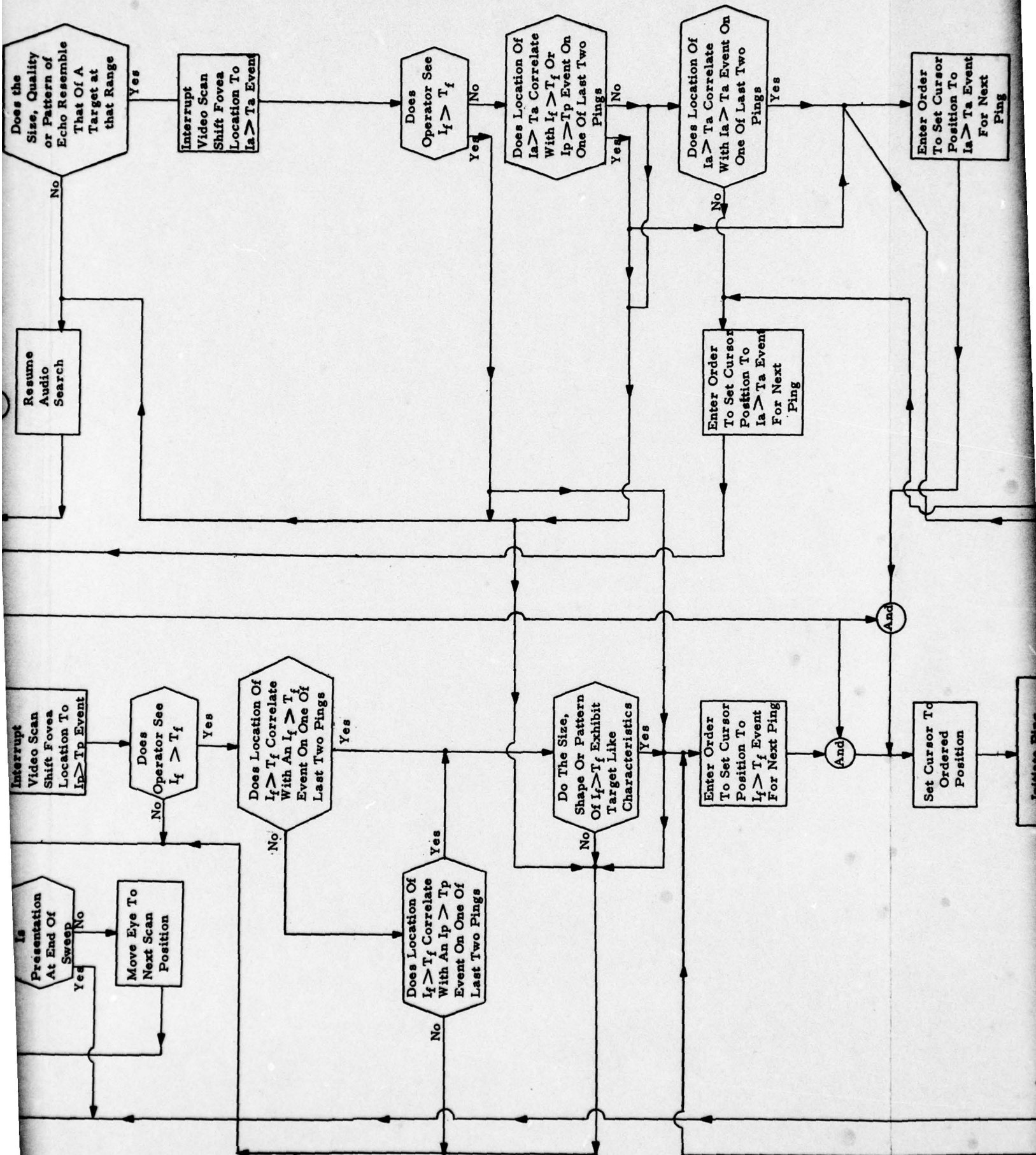
Now we will consider the audio channel with the operator listening to the returns on the cursor bearing. This development is based on the assumption that audio detection is based on two echo dimensions, intensity (or amplitude) and doppler (or frequency). There is a third important dimension, "quality," which everyone hears but no one can describe, much less quantify. It may be some combination of sub threshold intensity and doppler along with echo rise time. If some formulation of this echo characteristic can be devised, it will be included as a parallel audio alarm criterion. If he hears a return whose intensity or doppler exceeds his threshold for that

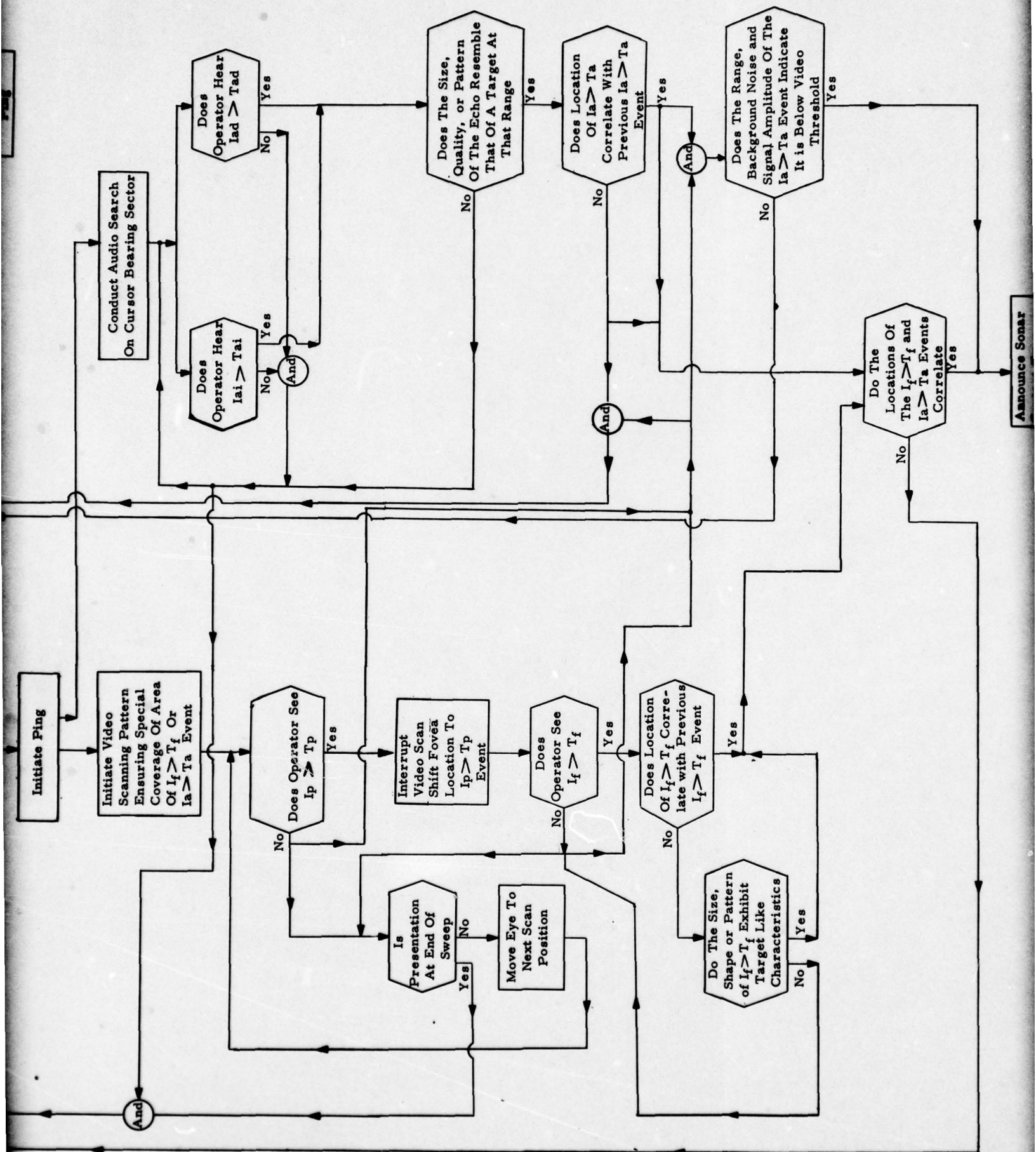
characteristic, and if the echo resembles that of a target at that range, the operator interrupts his video scan, and shifts his fovea to the location of the echo. If he sees a bright area with his fovea (a function of return intensity, decision and eye movement time, and phosphor brightness degradation) he has achieved correlation on a single ping, he orders a confirmation ping on the next transmission, and he continues his audio and video search for the rest of this transmission. If he does not see it, he determines if the location of the echo correlates with that of a video response on one of the last two pings. If so, he orders a confirmation ping on the next transmission. If not, he determines whether the location correlates with an audio return noted on one of the last two pings. If so, he orders a confirmation ping on the next transmission. If not, he orders that for the next transmission the cursor be trained to the bearing of this audio return, but that otherwise the video scan and audio search be normal. This last procedure is necessary to permit ping-to-ping correlation of audio only responses without degrading the overall video scan.

Next let us consider the sequence followed on a confirmation ping. In this case, the cursor bearing and audio search are on the bearing of a suspected contact and the video scan pattern is modified to provide special coverage of the area of the suspected contact. If the operator sees a bright area, he shifts his fovea to its location, hopefully a short eye movement on the confirmation ping. If he sees a contact, he determines if its location correlates with the previous video detection event. If it does, he seeks correlation with an audio response. If it does not, he determines if the new video detection has target-like characteristics. If not, he continues his scan. If so, he seeks audio correlation. If there is audio-video correlation, the operator announces "sonar contact" and a detection has been made. If there is no audio correlation of a video response, the operator attempts another confirmation ping. No video response not correlated with an audio response will be announced as a detection because of the sensitivity advantage and reliability advantage inherent in the audio system. However, if there is an audio response which correlates with a previous audio response but there is no video response, a detection will be announced if the background noise and signal amplitude indicate a possibility of the echo intensity being below video detection threshold.

The foregoing description, together with Figure 3, summarizes our understanding of the process of sonar detection. It involves a perception process which depends on the psychophysical capabilities of the human operator, the deployment of his sensory capability (eye fixation point, audio beam orientation), a subjective criterion which reflects his degree of "conservativeness" in permitting response to sensory stimulus, and the intensity







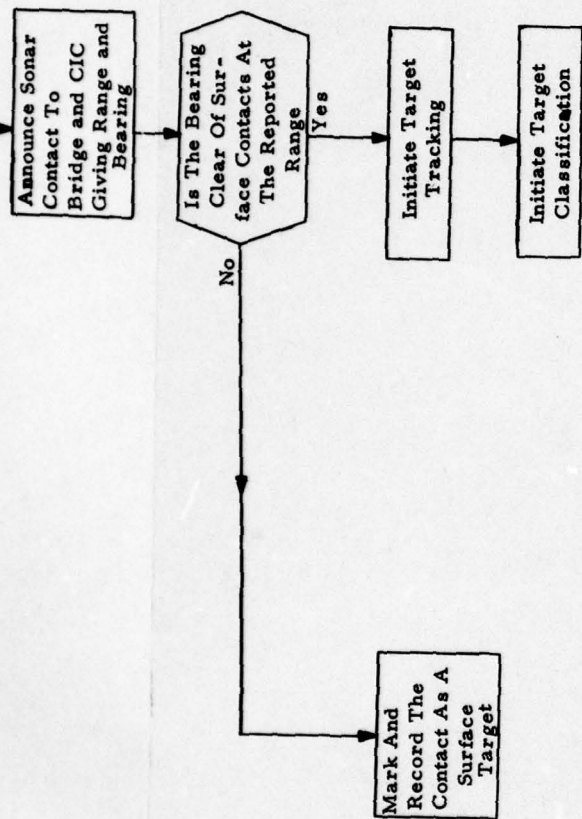


Figure 3. Operational sequence diagram, operator sonar detection

of the stimulus. Given a sensory reponse, or rather a series of such responses, detection involves a decision process which depends on stimulus persistence, position correlation of successive stimuli, intersensory correlation of stimuli, and pattern recognition. It is this decision process which is subject to objective organization control.

III. DETECTION MODEL

A. General Description

Figure 4 shows the overall simulation model used. The three major portions are:

- . the geometric submodel
- . the physical world submodel
- . the human observer submodel

Each of the three submodels is based on certain assumptions, requires certain input values and provides a particular output. By way of definition, a "run" consists of a series of targets, generated under a particular group of constraints, which are potentially detectable by the ASW ship. The constraints are input values to each section of the up-dated model. They would include such things as target minimum/maximum speeds, transmitted power level, scan policy, etc.

B. Geometric Submodel--Overview

The geometric submodel generates a series of vectors which represent the relative motion of targets and own ship. The geometric submodel makes a number of basic assumptions among which are:

1. All motion takes place in an infinitely large sea.
2. Targets are randomly distributed throughout this infinitely large sea. In general, the targets are considered to be uniformly distributed. However, it should be noted that the targets will not cross the maximum range circle at all bearings with equal probability, because of the effect of the ASW ship's velocity.
3. Target courses are generally set to be uniformly and randomly distributed relative to the ASW ship's course. (Without the loss in generality, the ASW ship's course is taken as due North.) Other course distributions of the target may be used in the model as well. For example, we have included in this report a special study of the case where the target moves counter-parallel to the ASW ship.
4. Targets maintain fixed speeds and direction throughout simulation.

Basic Assumptions

Infinite planar sea
Randomly dist. tgts.
Tgts. maintain fixed
speeds and directions

a is const.
Layer is Inf. Deep
SCD, Med. pulse and
 R max. are fixed
Viewing Dist. is fixed.

No vision during eye
movement
Constant glimpse
criterion factor
Scan policy only
interrupted by signals
of valid targets

Geometric
Submodel

Successive Target
Positions

Physical
World
Submodel

Visual Signal and
Noise Levels

Decision-
Maker
Submodel

Freq. Distributions
of Detection Ranges
(output)

Input Conditions

V_s limits
 V_t limits
 R max.
Random No. Root

S_t , Transm. power
 $V(V)$, Variation factor
 $V(RF)$, Range factor
COR, Correl. factor
 k , Brightness conver-
sion efficiency factor

Q_t } Detection Report
 Q_p } Factors
Scan policy
Fixation time
Glimpse criterion
factor

Figure 4. Simulation Model

5. Targets are potentially detectable as soon as they cross the circle of maximum range (i. e. , range scale setting) as set on the sonar stack.
6. Targets will not appear within the maximum range circle more than one at a time. However, this factor is "not known" to the operator model which continues to scan the entire scope after tentatively deciding that a target has been located.
7. The speeds of both the target and the ASW ship are distributed in a uniform random fashion between specified upper and lower limits. As limiting cases, the upper and lower limits may be the same for either the target or ship--in which case, the target's or ship's speed would be uniquely specified. It is anticipated that other non-uniform random distributions will be incorporated in the extended model to reflect the realities of different tactical situations.

The chief factors which must be defined prior to each run of the geometric submodel are:

1. Own ship's speed limits
2. Target speed limits (upper and lower)
3. The range scale setting of the sonar equipment, which is equivalent to the maximum range of interest in the geometric submodel
4. The initial random number index for random number generation.

Figure 5 shows the block diagram of the geometric submodel. The target's relative speed and heading are calculated from the ASW ship's speed and the target's true speed and heading, which are randomly selected. Then the target's minimum range is selected, which is the final factor needed to fully define the target's course. Next, the target's first position on the PPI is selected, based on the random time the target crosses the maximum range circle, relative to the start of the ping cycle. Successive target positions are calculated from the first random position as required by the physical world submodel and decision-maker submodel.

C. Physical World Submodel--Overview

The physical world submodel simulates the electrical, electronic and acoustic phenomena which affect the ASW detection problem. This portion of the model also makes certain basic assumptions:

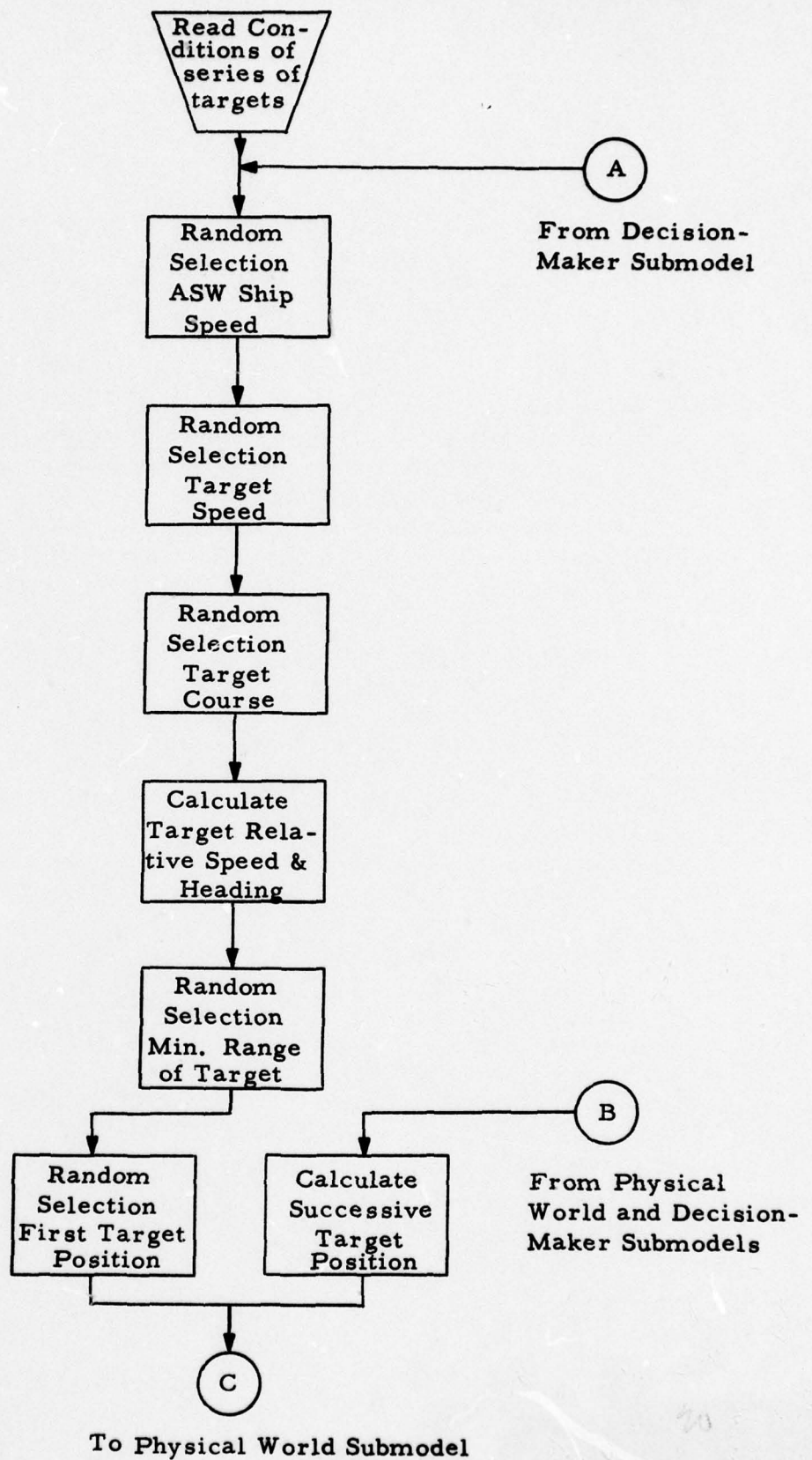


Figure 5. Geometric Submodel

1. The attenuation factor for sound in sea water is a constant. *
2. Water is isothermal and of infinite depth. (The extended detection model will incorporate the effects of thermal layers.)
3. There is no change made by the operator in equipment settings during the search phase, e. g., the equipment is set for SCD, "sum" brightening, and medium pulse length; and the range scale setting is fixed.
4. The operator performs his function at a fixed viewing distance from the sonar scope.
5. All detection is achieved visually. (The audio detection channels will be incorporated in the extended model.)
6. In the aggregate, signal strength variations which result in signal fading or enhancement are combined into a normal random variate with some correlation to the preceding signals. The standard deviation of received signals and degree of correlation to the preceding events may be controlled to simulate the effect of different environmental conditions. For example, placid seas would be simulated with small values of standard deviation of received signal. Shallow waters, rapid currents or other acoustic inhomogeneity may be simulated with low ping-to-ping correlation.
7. Variation factors are grouped in one of two categories; either range-dependent or range-independent.
8. Both the range-dependent and range-independent variation factors have the same rates of change.

The initializing factors for the physical world submodel are as follows:

1. transmitted power, S_t
2. range-independent variation factor, $V(I)$
3. range-dependent variation factor, $RF(I)$

*While this is not strictly true, the effects of variations are considered to be combined with other sources of signal strength variation--see item 6.

4. correlation factor, COR
5. CRT brightness conversion efficiency, k

Figure 6 shows the block diagram of the physical world submodel. It will be seen that the gain level is dependent on the effective range and the noise level. It will also be seen that the calculation of brightness excess is determined by one of three relationships, depending on whether the noise level, the signal level only, or neither level is below the saturation level of the scope.

D. Decision-Maker Submodel--Overview

The human observer or decision-maker submodel receives the output of the physical world submodel (which represents a visual signal) and "decides" whether or not a possible target is present. In the detection model, the decision-maker submodel does not determine classification or threat level of a possible target.

The decision-maker submodel involves certain basic assumptions:

1. The operator fixates on the CRT at a series of points in consecutive sequence. All "glimpsing" is done during times of fixation; conversely, while the operator's eyes are in motion they are unable to see a target.
2. The decision maker follows a specified scanning policy in regard to fixation of his eyes as they move from fixation point to fixation point on the CRT. He deviates from the scan policy only when the expanding range circle reaches the range of a target previously glimpsed. At that time, the operator will direct his attention to that meridian on the range circle which represents his estimate of where the target might be during the current "ping." It should be mentioned that the scanning policy may be stochastic in nature, i. e., a kind of random walk. Experimental work recently completed by Dunlap and Associates, Inc.,² indicated that both experienced and inexperienced operators tend to follow essentially random walk scan patterns when searching for targets on a PPI. To date all specified scanning policies used in the detection model program have been deterministic. This will be changed in the extended model to reflect the experimental findings.

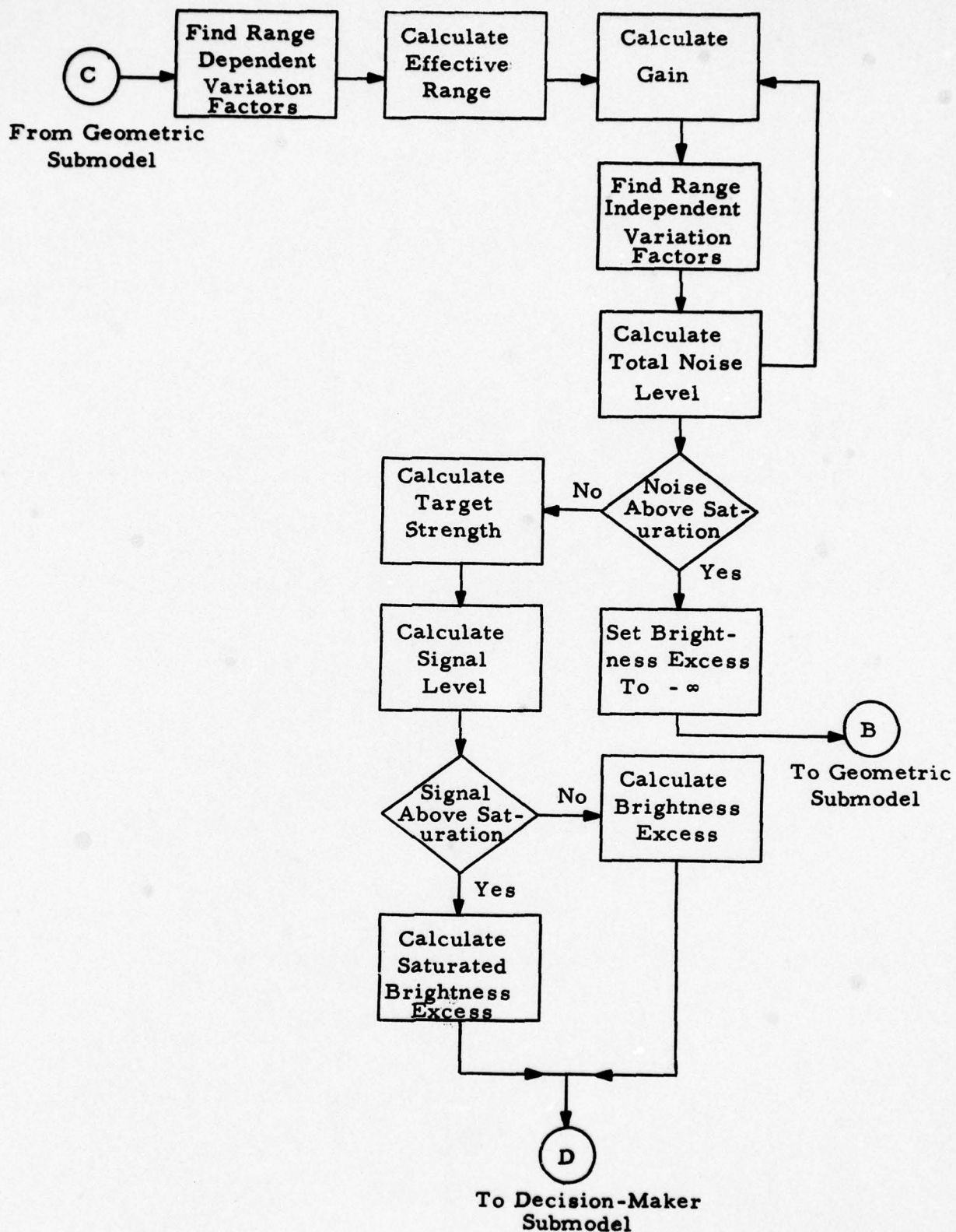


Figure 6. Physical World Submodel

- 1/ false alarm rate*
3. Only targets (not spurious noise spots) will cause an interruption in the scan policy. (We expect to include interruption in the scan policy by other than the true target signals in the extended model.)
 4. The probability that a target will be glimpsed by the operator (consciously recognized as a possible target) during an eye fixation is a function of its retinal position and brightness excess. The brightness excess is the target's brightness relative to the surrounding visual field. This assumption has been experimentally verified in a recent experiment.¹ The probabilistic function used in the model is based on the referenced report.
 5. The probability that a target will be glimpsed is also a function of an internal criterion used by the operator. In practice, the criterion may not be subject to full description by the operator; however, it may be measured in terms of the signal excess (corrected for retinal position) of a spot on the CRT that an operator would recognize as a target 50 percent of the time.

It is hypothesized that the operator's criterion has a value which depends on such things as his conservatism, the noise level on the PPI, the capacity of his short-term memory for recently glimpsed possible targets, his data handling capacity, as well as some psychophysical limitations. The lowest criterion, which represents a kind of threshold, was the criterion used in the referenced experiment.¹ The threshold criterion represents the case where operator pays absolutely no penalty for being wrong, and his memory and data handling capacity are exercised minimally (in the referenced experiment only one target was presented at a time and no distracting noise was present).

The model assumes that the operator's criterion is displaced from the minimum or threshold criterion by a specified displacement factor. The magnitude of this displacement is controlled as a parameter in the simulation, in order to investigate the sensitivity of detection performance to this factor. The displacements considered correspond to glimpsing a threshold level signal with a probability of .0001, .001, .01, .1, .5 (no displacement). This displacement factor is called the Glimpse Criterion.

6. The decision maker decides that a target is present if his last glimpse of the target is foveal (i. e., he sees it well enough to recognize its target-like appearance) and if he has glimpsed the target a specified number of times out of the last group of pings. As an example of these later criteria, during a "hot war" situation the sonar operator, on his own initiative or by instruction, might

announce a sonar contact if he sees a target in two out of the last three pings. During peace time when the ASW ship has important non-ASW functions to perform, the sonar operator may not announce a possible submarine unless he sees a target on 10 out of the last 12 pings. This objective criterion is one which can be controlled and specified by the operator's superiors. Such criteria, being objective, are thus quite different from the internal criterion which an operator uses to determine whether or not a slight brightening of the scope on any one ping is indeed a possible target.

The decision-maker submodel will have as inputs:

1. a scanning policy
2. fixation time
3. glimpse criterion factor
4. detection announcement factors, i. e., the number of glimpses, Q_p out of a total number of the last Q_t glimpses.

Figure 7 shows the block diagram of the decision-maker submodel. If the operator's eyes are in motion and not enough time remains for a later glimpse during the current ping, the submodel calls for the next target position. The next block, "find next fixation point" may be entered via several paths and requires some explanation. "Finding the next fixation point" depends on the scan policy which specifies the next fixation point, unless it is overridden by a predicted target location (due to a successful peripheral fixation during the current ping, or glimpse during a prior ping). If all detection criteria are met, the detection range and time are incorporated with those of prior runs for printout when the series of targets have been run.

E. Current Program Flow Chart

The block diagram submodels shown in Figures 5, 6, and 7 comprise the detection model in its current state of development. The submodels are explained more fully and their mathematical bases are discussed at length in Sections V, VI, and VII. Development of the computer program to implement the detection model quite naturally is not at as an advanced state as the detection model itself. Figure 8 shows the block diagram of the detection model computer program. It selects parameters to describe the initial

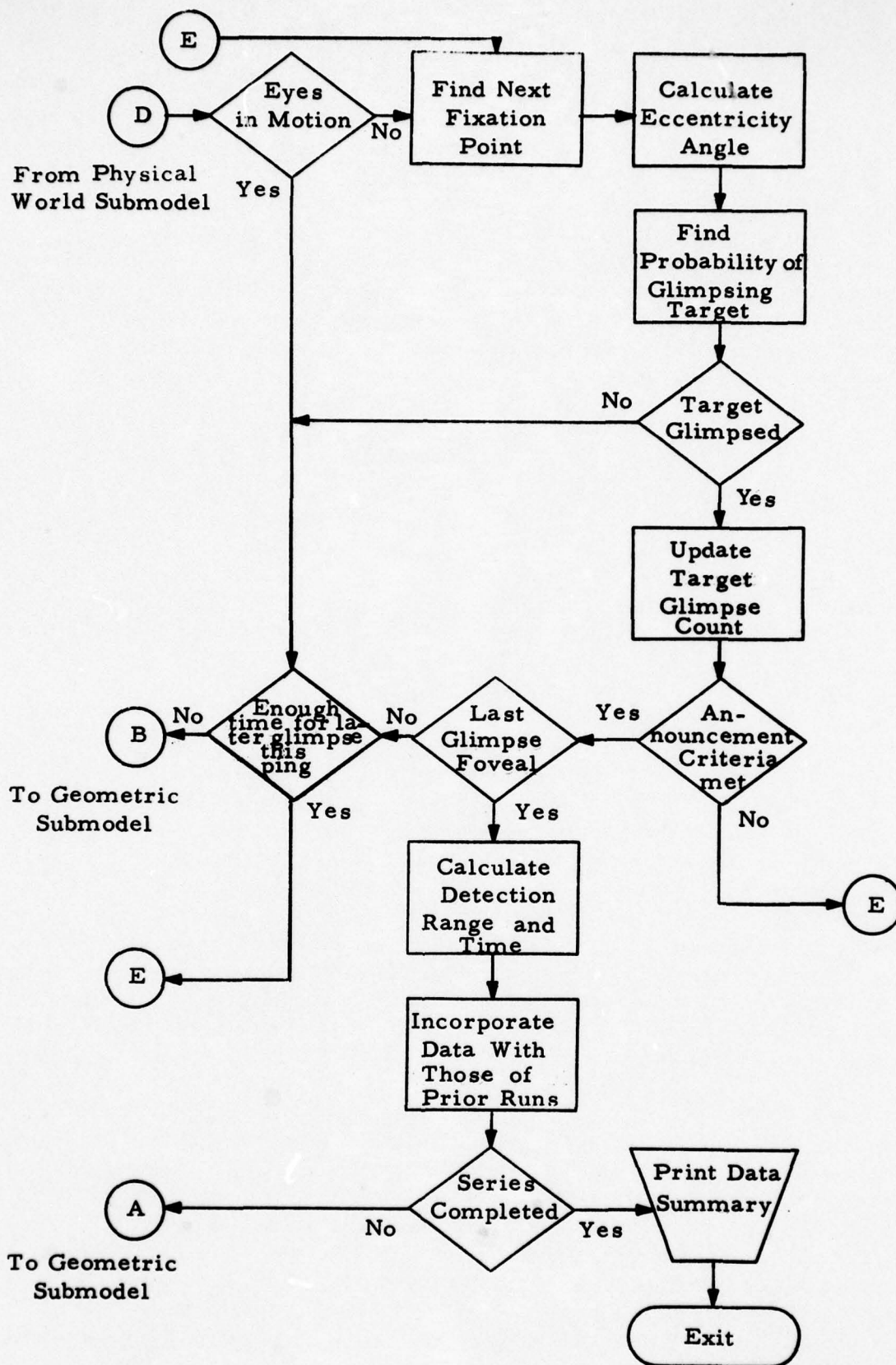


Figure 7. Decision-Maker Submodel

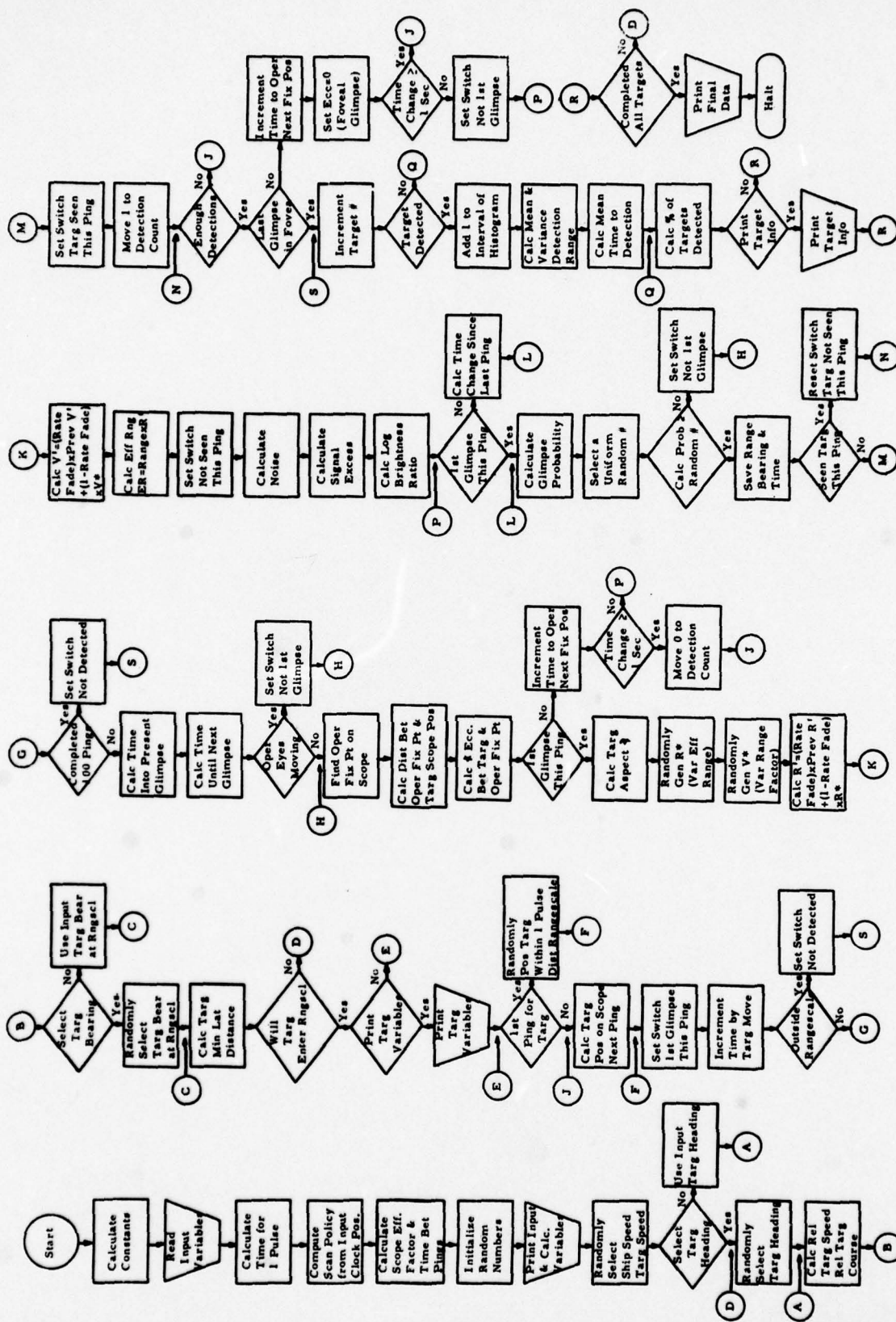


Figure 8. Detection Model Program

relative target geometry from uniform distributions (special cases of which are single valued distributions). Further, it does not yet consider the effects of saturation but assumes the gain level is set to preclude noise or signal saturation. And lastly it describes the decision-maker logic in a somewhat simplified manner by assuming constant eye movement time and ignoring anticipated target locations due to glimpses of prior pings. The block diagram was prepared to closely follow the program itself. It thus reflects to some extent the historical development pattern of the program rather than the more tidy (à posteriori) descriptions of the conceptual model.

Section VIII summarizes the results of the program applications to date. These applications indicate areas that need to be developed in the extended model and also provide some interesting, though tentative, conclusions.

F. Use of Monte Carlo Techniques

It is important to note that at each decision point in this model we could not work with probability values and carry them on to the next decision point. The reason for this is the large number of decision points and the even larger number which is anticipated in the extended model. To keep track of all conditional probability values and operate with all of them would make for an impossibly burdened model. The technique we have adopted is the one familiarly known as the Monte Carlo technique which forces a decision at every point where the decision is considered probabilistic. For example, if the probability that the operator would see a particular target under a given set of conditions in his fovea is .80, the program selects a number from the uniform random number generator and compares it to .80. If the number selected is indeed below .80, the model "did see the target" and follows the decision tree branch which corresponds to a situation where the operator did indeed see a target. Since the uniform random number generator will provide a number below .80 80 percent of the time, the probability that the program will follow the "did see" branch of the tree equals the probability that the operator did in fact see the target. Examining the results of many targets, we can see the pattern that results from the many probabilistic decision points and stochastic phenomena. Monte Carlo techniques thus make possible the analysis of models that would be otherwise computationally intractable.

G. Summary of Symbol Definitions

The symbols used in the description of the detection model are summarized for convenience in Table II.

Table II
Symbol definitions

Symbol	Definitions
a	Attenuation coefficient of sound in the ocean medium in db per yards.
$B(t)$	Target brightness to seconds after excitation.
BE	Brightness excess
c	Speed of sound, assumed constant over time and position.
COR	Correlation factor which is a constant for each run and can vary from 0 to 1.
e	Signal voltage
E	Electrical signal of acoustic origin, in db.
$E(I)$	Received signal strength during the I-th ping, in db.
E_{bias}	Grid bias voltage.
ECC	Angle of eccentricity in degrees.
E_{co}	Scope's cutoff voltage.
E_{d2}, E_{d1}	Grid voltages (measured above cutoff).
g	Gain of the sonar receiver in db.
G	Fixed portion of the gain, in db.
g_r	Voltage gain of the receiver as a ratio, i. e., $g = 20 \log g_r$.
I_2, I_1	Scope brightness at two different grid voltages.
I_a	Intensity measured with the scope illuminated by ambient light only.

Table II (Continued)

Symbol	Definitions
I_e	Intensity measured without ambient light, but with the scope excited by electron beam.
I_n	Scope brightness due to acoustic noise superimposed on electrical noise.
I_{e+a}	Intensity measured with both ambient illumination and scope excitation by electron beam.
I_{n+a}	Intensity of electrical noise and ambient lighting noise.
I_{e+n}	Intensity of the electrical signal.
I_{s+n}	Intensity of signal superimposed on noise.
I_{e+n+a}	Intensity of the electrical signal superimposed on electrical noise and ambient lighting noise.
ΔI	Intensity of a spot with signal, above the intensity of the surrounding noise of acoustic origin.
ΔI_a	Intensity of spot with signal, above the intensity of the surrounding noise originating from both acoustic noise and significant amounts of ambient lighting.
k	Conversion efficiency of the scope.
n	Acoustic noise voltage.
N	Electrical noise of acoustic origin, in db.
$N(I)$	Overall noise factor, in db.
$NR(I)$	Reverberation noise in terms of db.
$NRPR(I)$	Reverberation noise in terms of a power ratio.

Table II (Continued)

Symbol	Definitions
NS (I)	Ship's noise in terms of db.
NSPR (I)	Ship's noise in terms of a power ratio.
Q_p, Q_t	Detection announcement factors.
R	Range scale setting, which is taken to be the radius of the maximum circle of visibility.
R (I)	Value of the true geometric range during the I-th ping.
R_{n+1}, R_n	Ranges of the target when struck by pings numbered $n+1$ and n , respectively.
R'_o	Range of the target at T_o' .
$R' (I)$	Effective range of the target.
RF (I)	Range factor for the I-th ping.
RF*	Normal random variate whose expected value is 1.0 and whose variance is $V(RF)$.
RN.	A random number whose distribution is assumed to be uniform, unless otherwise specified in the test.
s	Signal level for saturation of the scope.
S	Signal level for saturation of the scope, in db.
S_t	Average transmitted signal strength, in db.
t	Time since removal of a disabling pulse on the receiver.
t_{n+1}, t_n	The times that pings numbered $n+1$ and n , respectively, strike the target. These times are measured relative to when the target first enters the maximum range circle.

Table II (Continued)

Symbol	Definitions
T	Time constant of the R-C circuit which governs the TVG function.
T_p	Time between transmission of sonar pings.
T_o'	The time a second ping would strike a target first illuminated at maximum range, R .
$T(I)$	Target strength for the I -th received signal, in db.
TVG	Time varying portion of the gain, in db.
$V(I)$	Normal random variate whose expected value is zero and whose variance is a supplied constant $V(V)$.
V_s	Magnitude of the velocity vector of the ASW ship.
V_t	Magnitude of the velocity vector of the target.
V_r	Magnitude of the velocity vector of the target relative to the ASW ship.
X	Distance of actual glimpse along an X-axis.
\hat{X}	Anticipated distance of glimpse along an X-axis.
X_n, Y_n	Coordinates of the position of the target at ping, n .
z	Distance along the maximum range circle's diameter that is perpendicular to Φ
Z	Normalized parameter in the gaussian distribution.
β_o	Relative bearing of the target as it crosses the circle of radius R .
Φ	Angle between the direction of V_s and V_r , i. e., the relative target heading.

Table II (Continued)

Symbol	Definitions
$\phi(I)$	Target aspect angle relative to the line of sight, (the angle between the heading of the target and its relative bearing) on the I-th ping.
ϵ	Angle between the courses of the ASW ship and the target.

IV. GEOMETRIC SUBMODEL

The mathematical development of the geometric portion of the model is based on an application of Koopman's⁴ work to our model. Much of the development in this section is a summary of the geometric model described in a previous report³. Where noted, the previous development was expanded upon for purposes of clarification.

A. Relative Velocity Vector

Examining the vector diagram (Figure 9), relating V_s , V_t , and V_r , we may derive the magnitude and direction of V_r and Φ by trigonometrical means.

$$V_r = \sqrt{V_t^2 + V_s^2 - 2 V_s V_t \cos \Theta} \quad (1)$$

$$\Phi = \arctan \left(\frac{V_t \sin \Theta}{V_t \cos \Theta - V_s} \right) \quad (2)$$

where

V_s = magnitude of the velocity vector of the ASW ship

V_t = magnitude of the velocity vector of the target

V_r = magnitude of the velocity vector of the target relative to the ASW ship

Θ = angle between the direction of V_s and V_t

Φ = angle between the direction of V_s and V_r

In a particular run the values of V_r and Φ may be calculated by selecting random values of V_t , V_s and Θ , as follows:

$$V_s = \min V_s + (RN1) (\min V_s - \max V_s)$$

$$V_t = \min V_t + (RN2) (\min V_t - \max V_t)$$

$$\Theta = (RN3) 2\pi$$

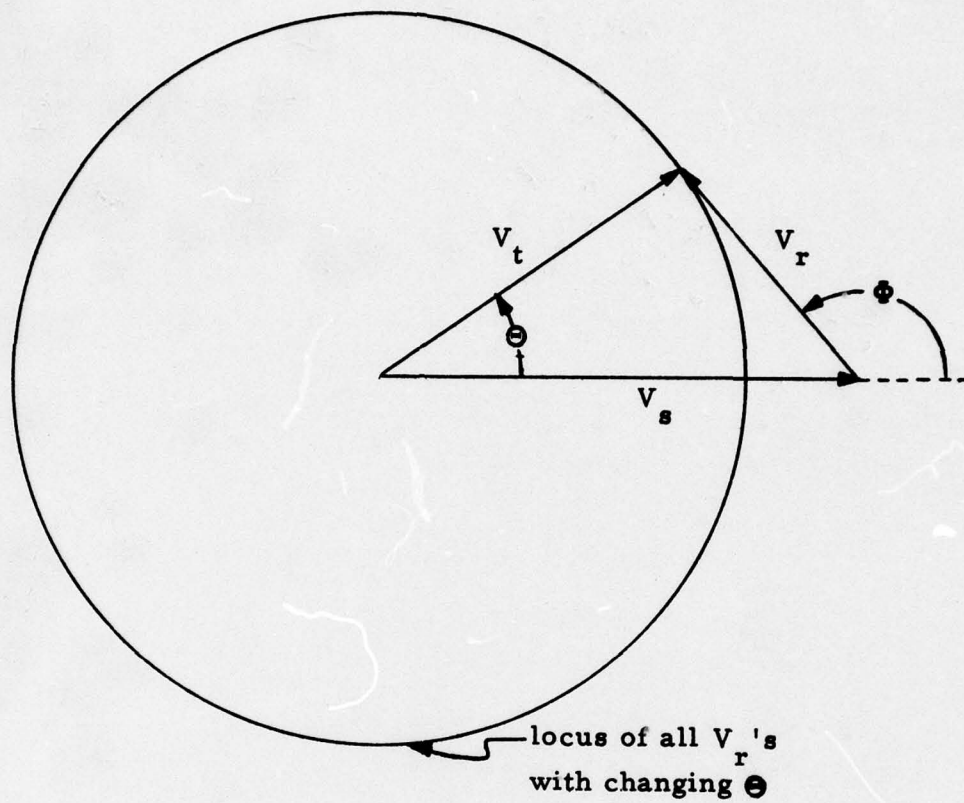


Figure 9. Vector Diagram of V_s , V_t , and V_r .

RN1, RN2, RN3 are pseudo-random numbers distributed between zero and one. In most of the runs to date RN1, RN2 and RN3 have been uniformly distributed. However, the extended detection model will contain other stochastic distributions based on scenarios of typical ASW encounters.

B. Bearing Angle

It was previously demonstrated³ that for uniformly distributed targets whose courses are also uniformly distributed between zero and 2π

$$Z = 2(RN4) R$$

$$\beta_0 = \Phi - \arcsin\left(\frac{Z - R}{R}\right)$$

where

Z = distance along the diameter of the maximum range circle (see Figure 10)

R = range scale setting, which is taken to be the radius of the maximum range circle

β_0 = bearing of the target as it crosses the maximum range circle

RN4 is a random number between zero and one whose distribution may or may not be uniform.

In general, it should be noted that β_0 is not a uniform random variable; but it is a function of V_s , V_t , Θ and z all of which may be uniform random variables. When the four independent random variables are uniformly distributed, β_0 may be expected to occur most often in the direction in which the ASW ship is heading. Preliminary work by Dunlap and Associates, Inc., with the ASW ship in a screen defending against transiting targets indicates that β_0 tends to follow a bimodal distribution. Further developments resulting from the non-uniform distributions of the four independent variables will be included in the extended detection model.

C. Detectable Targets' Position

When a target enters the maximum range circle, it is potentially detectable only after the expanding range circle intersects the target's relative course vector. That is, the target appears as a series of fading spots on the PPI scope.

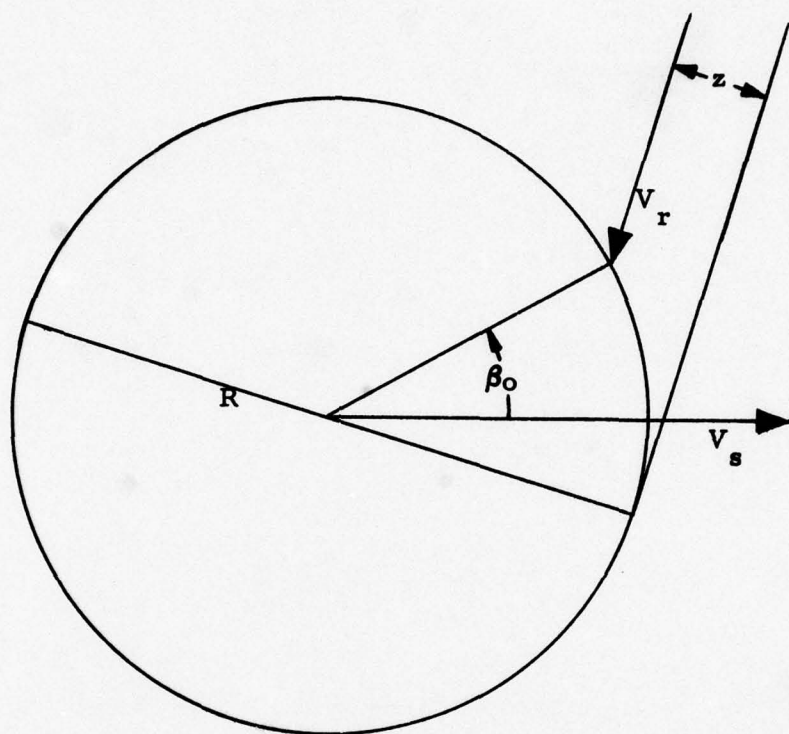


Figure 10. Initial Bearing Angle

The geometric model provides the time and position of these points, as well as the target's relative velocity. All of these characteristics of the target will have a bearing on whether a particular target is deemed to have been detected in subsequent portions of the model.

As the target progresses along its track, it will reflect sonar energy periodically. The time between two successive reflections may be stated as:

$$t_{n+1} - t_n = T_p + \left[\frac{R_{n+1}}{C} \right] - \left[\frac{R_n}{C} \right] \quad (3)$$

where

t_{n+1} , t_n = times that pings numbered $n+1$ and n , respectively, strike the target. These times are considered to start when the target first enters the circle of visibility.

T_p = time between transmission of sonar pings

R_{n+1} , R_n = ranges of the target when struck by pings numbered $n+1$ and n , respectively.

c = speed of sound, assumed constant over time and position.

The time between transmission of sonar pings is assumed to be equal to the time it takes the leading edge of the sonic pulse to reach and return from the maximum range of the circle of visibility. That is, there is assumed to be no dwell time between pings. Accordingly,

$$T_p = \frac{2R}{c} \quad (4)$$

In the model, the target is first ensonified some time after it first enters the maximum range circle. The time of the first ensonification is a uniformly random variable which falls between the time the target first enters the maximum range circle and the time a second ping would strike the target if it were first ensonified at the maximum range. The time bounds of the first ping are taken as zero and T'_0 . From (3) and (4),

$$T'_0 = T_p - \left(\frac{R - R_0'}{C} \right) = \frac{R + R_0'}{C} \quad (5)$$

where,

T_o' = time a second ping would strike a target first
ensonified at maximum range, R.

R_o' = range of the target at T_o'

Thus, the time of the first ensonification is:

$$t_1 = RN5 (T_o') = RN5 \left(\frac{R + R_o'}{C} \right) \quad (6)$$

where,

RN5 = random number, uniformly distributed between zero and one.

It follows that the time of ensonification by the n'th ping is:

$$t_n = t_1 + (n-1) T_p - \sum_{i=1}^{n-1} \left(\frac{R_i - R_{i+1}}{C} \right) \quad (7)$$

Substituting the explicit expression for the summation, and (4) and (6) in this last expression,

$$t_n = RN5 \left(\frac{R + R_o'}{C} \right) + 2 (n-1) \frac{R}{C} - \left(\frac{R_1 + R_n}{C} \right) \quad (8)$$

Referring to Figure 11, it may be seen that:

$$(R_o')^2 = R^2 + \left(\frac{V_r}{C} \right)^2 (R + R_o')^2 - (2R) \left(\frac{V_r}{C} \right) (R + R_o') \cos (\Phi - \beta_o) \quad (9)$$

and,

$$(R_1)^2 = R^2 + (RN5)^2 \left(\frac{V_r}{C} \right)^2 (R + R_o')^2 - (RN5) (2R) \left(\frac{V_r}{C} \right) (R + R_o') \cos (\Phi - \beta_o) \quad (10)$$

and

$$R_n^2 = R^2 + t_n^2 V_r^2 - 2 R t_n V_r \cos (\Phi - \beta_o) \quad (11)$$

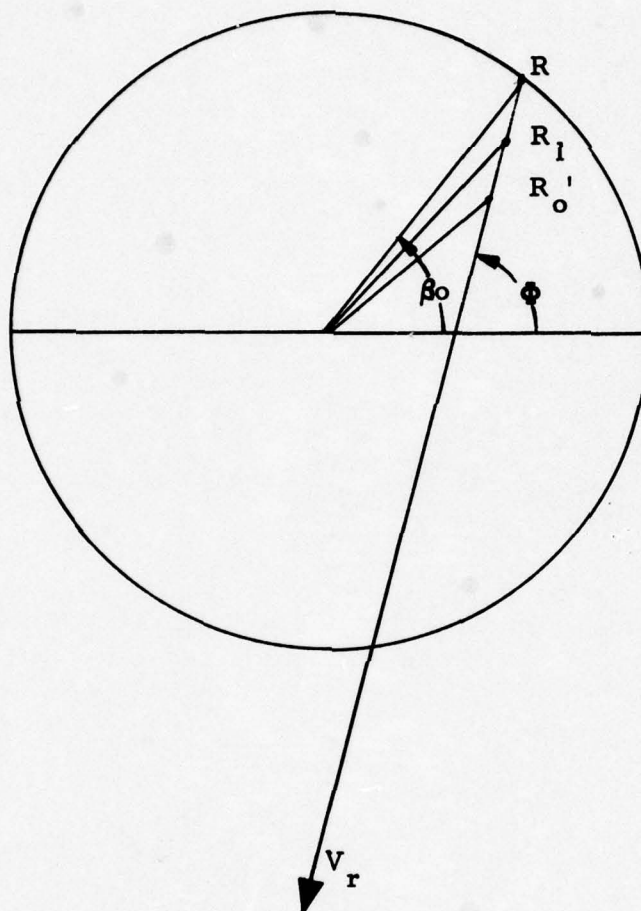


Figure 11. Initial Target Position on PPI.

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Relations (9) and (10) may be used to reduce (8) to an expression of t_n as a function of V_r/C , n , R , and R_n , as follows:

$$t_n = f(V_r/C, n, R, R_n) \quad (12)$$

Expression (11) and (12) then define t_n and R_n in terms of V_r/C , n , R , and R_n . However, if we recognize that V_r/C is small, (never more than .02 and typically about .01) expressions (7) and (8) reduce to:

$$R \cong R_o' \cong R_1 \quad (13)$$

and (6) reduces to:

$$t_n = T_p (RN5) + (n-1) T_p - \left(\frac{R + R_n}{C} \right) \quad (14)$$

or,

$$t_n = T_p (RN5 + n - 3/2) - \left(\frac{R_n}{C} \right) \quad (15)$$

From (11),

$$\frac{R_n^2}{C^2} = \left(\frac{R}{C} \right)^2 + t_n^2 \left(\frac{V_r}{C} \right)^2 - 2 \left(\frac{R}{C} \right) t_n \left(\frac{V_r}{C} \right) \cos(\Phi - \beta_o) \quad (16)$$

and from (15),

$$\left(\frac{R_n}{C} \right)^2 = \left[\frac{R}{C} (2RN5 + 2n-3) - t_n \right]^2 \quad (17)$$

subtracting (17) from (16),

$$\begin{aligned} \left(\frac{R}{C} \right)^2 \left[(2RN5 + 2n-3)^2 - 1 \right] - t_n \frac{2R}{C} \left[2RN5 + 2n-3 - \left(\frac{V_r}{C} \right) \cos(\Phi - \beta_o) \right] \\ + t_n^2 \left[1 - \left(\frac{V_r}{C} \right) \right] = 0 \end{aligned} \quad (18)$$

Then, since $\frac{V_r}{C} \ll 1$, for $n > 1$:

$$t_n^2 - t_n \left[\frac{2R}{C} (2RN5 + 2n-3) \right] + \left(\frac{R}{C} \right)^2 \left[(2RN5 + 2n-3)^2 - 1 \right] = 0 \quad (19)$$

Solving this quadratic equation for t_n ,

$$t_n = \frac{R}{C} (2RN5 + 2n-3) \pm \frac{R}{C} \sqrt{(2RN5 + 2n-3)^2 - (2RN5 + 2n-3)^2 + 1} \quad (20)$$

or,

$$t_n = \frac{R}{C} \left[(2RN5 + 2n-3) \pm 1 \right] \quad (21)$$

By selecting the positive root, (21) is seen to apply to the case of $n = 1$ as defined in (6) (with the constraint of (3)). Further, by continuing with the positive root for $n = 2, 3, \dots$, (21) would describe successive values to t_n without conflict for all values of n . Accordingly,

$$t_n = T_p (RN5 + n-1) \quad (22)$$

We are now able to list the coordinates of the position of the target on the n 'th ping,

$$x_n = T_p (RN5 + n-1) V_r \cos \Phi + R \cos \beta_o \quad (23)$$

$$y_n = T_p (RN5 + n-1) V_r \sin \Phi + R \sin \beta_o \quad (24)$$

and,

$$R_n = \sqrt{R^2 + V_r^2 T_p^2 (RN5 + n-1)^2 - 2R V_r T_p (RN5 + n-1) \cos (\Phi - \beta_o)} \quad (25)$$

$$\beta_n = \arctan \left[\frac{T_p (RN5 + n-1) V_r \sin \Phi + R \sin \beta_o}{T_p (RN5 + n-1) V_r \cos \Phi + R \cos \beta_o} \right] \quad (26)$$

It should be noted that these last five relations are equivalent to those shown, without as full a development, in a previous report.³

D. Operations Sequence

The usual sequence of operation for the geometric submodel of the detection model is listed as follows:

a. Set the initial conditions

b. Select Θ , the initial target course

$$\Theta = (\text{RN1}) 2\pi$$

c. Select V_s , the ASW ship's velocity

$$V_s = (\text{RN2}) (\text{maximum } V_s - \text{minimum } V_s) + (\text{minimum } V_s)$$

d. Select V_t , the target's velocity

$$V_t = (\text{RN3}) (\text{maximum } V_t - \text{minimum } V_t) + (\text{minimum } V_s)$$

e. Calculate

$$\Phi = \arctan \left(\frac{V_t \sin \Theta}{V_t \cos \Theta - V_s} \right)$$

f. Calculate $|V_r|$, the targets' relative speed

$$V_r = V_t - V_s = \sqrt{V_t^2 + V_s^2 - 2 V_s V_t \cos \Theta}$$

g. Select z , the distance along the range diameter, normal to V_r that the target enters PPI scope

$$z = (\text{RN4}) (2R)$$

h. Calculate β_o , the initial bearing of the target

$$\beta_o = \Phi + \arcsin \frac{R-z}{R}$$

i. Calculate the position and time of the target on ping n .

$$x_n = T_p (\text{RN5} + n-1) V_r \cos \Phi + R \cos \beta_o$$

$$y_n = T_p (\text{RN5} + n-1) V_r \sin \Phi + R \sin \beta_o$$

$$t_n = T_p (\text{RN5} + n-1)$$

- j. Input target position and time information to the physical world submodel.

Several special features of the geometric submodel are worthy of mention. It is possible to vary the number of targets for any particular set of tracking simulation runs. The number of targets is read into the program with other program input information. The stochastic distributions of V_s , V_t , Θ , and z can be made to follow uniform distributions or other specialized distributions as dictated by analysis of typical tactical situations. In particular, the geometric submodel offers the flexibility of having constant target bearing and target heading values replace the randomly generated values which would normally be used when making simulation runs. The specific target heading and/or bearing values desired may be inserted into the simulation model with other input data.

V. PHYSICAL WORLD SUBMODEL

A. Functions

The physical world model encompasses the following functions:

- . sonar transmitted signal
- . acoustic transmission of the signal through the ocean to the target
- . reflection of the signal from the target
- . transmission of the signal from the target back to the sonar receiver
- . spurious reflection of transmitted signal
- . conversion of the received acoustic signal and noise to a visual display on the sonar scope
- . comparison of visual signal and visual noise
- . various forms of gain control
- . phosphorescent decay of visual display

B. Received Signal Strength

The activity of the physical world model starts at the time a target crosses the maximum range circle (i. e., range scale setting of PPI). Provision is made for this time to be randomly selected relative to the start of any particular ping. The position of the target on the scope is determined by the output of the geometric model and the expanding range circle. Several factors are considered in determining the magnitude of $E(I)$, the received signal strength during the I -th ping. (These factors are related in equation (1).) Most of the factors are present as fixed or deterministically set values. However, in recognition of the many factors and complexities not included in the relation, the magnitude of $E(I)$ is perturbed by two random variables. One random variable includes the range-related factors; while the second perturbs the value of $E(I)$ in lieu of the host of non-range related factors. As is traditional when accounting for the effects of numerous variables of indeterminate distribution, both factors are considered to follow normal

distributions. Recognizing that many of the factors manifest some degree of autocorrelation, both of the perturbing random variables take a form which permits control of their ping-to-ping correlation. The kinds of factors that would affect $E(I)$ as a function of range are the attenuation and refraction characteristics of the sea, the changing ray paths between ASW ship and target, the effect of wind speed and direction on surface reverberation, etc. Non-range related factors that are not explicitly covered in equation (1) include changes in the effective transmitted power level that occur as the ASW ship rolls, pitches and heaves in the sea, the abrupt changes in target reflectivity as a function of minute changes in the impinging angle of acoustic energy, the effects of sea state on the amount of bubbles and other soundwave impediments in the immediate vicinity of the ASW ship, the position of the target relative to the thermal layer, etc. Some of these factors we plan to isolate and treat more specifically in the extended model. However, it is anticipated that there will always be a substantial body of unknowns which would be grouped in one of the two random variables. As major factors are removed from the aegis of the "catch all" random variables, the magnitude of their standard deviation would be reduced and possibly their mean and degree of autocorrelation would be changed.

It should be noted that the inclusion of the random variables in the relation governing $E(I)$ permits the model to incorporate phenomena whose general effects on signal level are well known to experienced Navy personnel, but whose exact functional relationship is not well understood. Thus, the model can simulate rapid changes in effective range typical of strong currents, sharp temperature and density gradients, and rough weather. Alternatively, the model can simulate very low rates of change as when the ASW ship and target are in relatively deep, placid, isothermal waters. Aside from the rates of change of the random factors, the model can simulate different magnitudes of random change. Thus, it would simulate differently ASW ships which are part of a noisy convoy and ships that are part of a small SAU. The received signal at the scope is described by the sonar range equation:*

$$E(I) = St - 2\alpha R'(I) - 40 \log R'(I) + T(I) - V(I) + g \quad (1)$$

St = average transmitted signal strength. It is a value which can be varied for a particular run.

*See, for example, reference 5. Equation (1) is modified slightly by the addition of the variation factors and the term for gain.

a = attenuation coefficient of sound in the ocean medium. We have assumed that this takes on a value of .0005db per yard. The value selected is the same used in our old model, and represents an average from published values (5), (6), (7).

R'(I) = effective range of the target. That is to say, it is the apparent range that a target possesses in so far as its signal strength is concerned. R'(I) is taken to be different from the true geometric range, R, due to the stochastic variations in transmitted signal, attenuation, refraction, signal scatter, and the like. The value R' is made to deviate from the value of R in a normally random fashion.

$$R'(I) = R(I) \cdot RF(I) \quad (2)$$

R(I) = value of the true geometric range during the I-th ping.

RF(I) = value of a varying coefficient whose expected value is 1.0. The value of RF(I) is determined by the following formula:

$$RF(I) = (COR) RF(I-1) - (1-COR) RF^* \quad (3)$$

COR = correlation factor. It is constant supplied for each run which can vary from 0 to 1. To simulate cases where environmental conditions would lead to rapid changes in effective range, the value of COR would be low, approximately .1 or .2. Cases where environmental conditions would produce very slow changes in effective range would be simulated by setting the value of COR to approximately .8 or .9.

RF* = normal random variate whose expected value is 1.0 and whose variance is V(RF). The value of V(RF) would be supplied for a particular run. A typical value selected might be .15.

T(I) in equation (1) for received signal represents the target strength. The expected value of T is shown in (4). It represents an average of data from several sources^{5, 6, 8, 9}.

The magnitude of T varies between 12 db (for bow and stern aspects) and 25 db (for beam aspects).

$$T = 12 + 12 \left| \sin \phi(I) \right| \quad (4)$$

where,

$\phi(I)$ = target aspect angle relative to the line of sight, (the angle between the heading of the target and its relative bearing on the I-th ping).

$V(I)$ in equation (1) represents the non-range dependent variation factor. It encompasses such phenomena as rising and falling of transmitted signal due to uncontrollable equipment drift, variation in target reflectivity over and above the expected value due to the target aspect angle, as well as all other non-range related sources of variation in the received signal. The value of $V(I)$ is determined by the following relationship:

$$V(I) = (COR) V(I-1) + (1-COR) V(I)^* \quad (5)$$

COR is defined above.

$V(I)^*$ = normal random variate whose expected value is 0 and whose variance is a supplied constant, $V(V)$. The value of $V(V)$ selected for targets run to date has been 2 db.*

g in equation (1) represents the gain of the sonar receiver. It consists of a fixed and time varying portion, viz,

$$g = G + TVG \quad (6)$$

or,

$$g = G + 10 \log (1 - \exp (-t/T)) \quad (7)$$

*The value of $V(V)$ selected results in a signal to noise ratio no more than 4 times nor less than 1/4 the expected value, 99.7% of the time, due to the range independent factors.

where,

G = fixed portion of gain, and reflects the setting of the master level control.

TVG = time varying portion of gain.

t = time since removal of a disabling pulse on the receiver

T = time constant of the R-C circuit which governs the TVG function.

C. Time Varying Gain

The value of T in the SQS-23 is 20 seconds or .046 seconds, depending on the noise level. When the reverberation level is high, T is set equal to 20 seconds and the gain increases slowly with time. When the reverberation level is low, T is set equal to .046 seconds and the gain level rapidly rises to the level set by the MCL.

The TVG function is described in Figure 12. It will be seen that the TVG function can follow four different typical curves which represent four different typical cases. The first curve depicts the situation when the reverberation or noise level is very low, the second curve shows the situation when the reverberation is excessively high. Curve three shows the instance with typical noise and the master level control set at its optimum value. Curve four shows the situation where reverberation is very uneven due to gross non-homogeneity in the ocean environment. This could also be caused by gross changes in the noise level due to intermittent noise sources from an adjacent ship or an intermittent noise source on the ASW ship itself. Our interest in TVG is primarily as it affects the optimal gain settings. We plan to include provisions for adjusting the gain settings in the extended model.

D. Received Noise

Received noise is composed of the ASW ship's noise and the reverberation of the ocean. We have described reverberation, $NR(I)$, as a 0db strength target in the current state of our model development. We expect to describe reverberation more specifically in later models, taking into account both surface and bottom reverberation as separate factors. We have had some very preliminary indication that the model's current value of 0db is somewhat conservative based on sea state 3, a wind state of 15 knots, and the Chapman-Harris¹⁰ equations for surface scattering, or the Mackenzie¹¹ curves for bottom reverberation. For the present, the model may be considered to take into account non-zero db reverberation as part of the random factors included in $V(I)^*$ and RF^* .

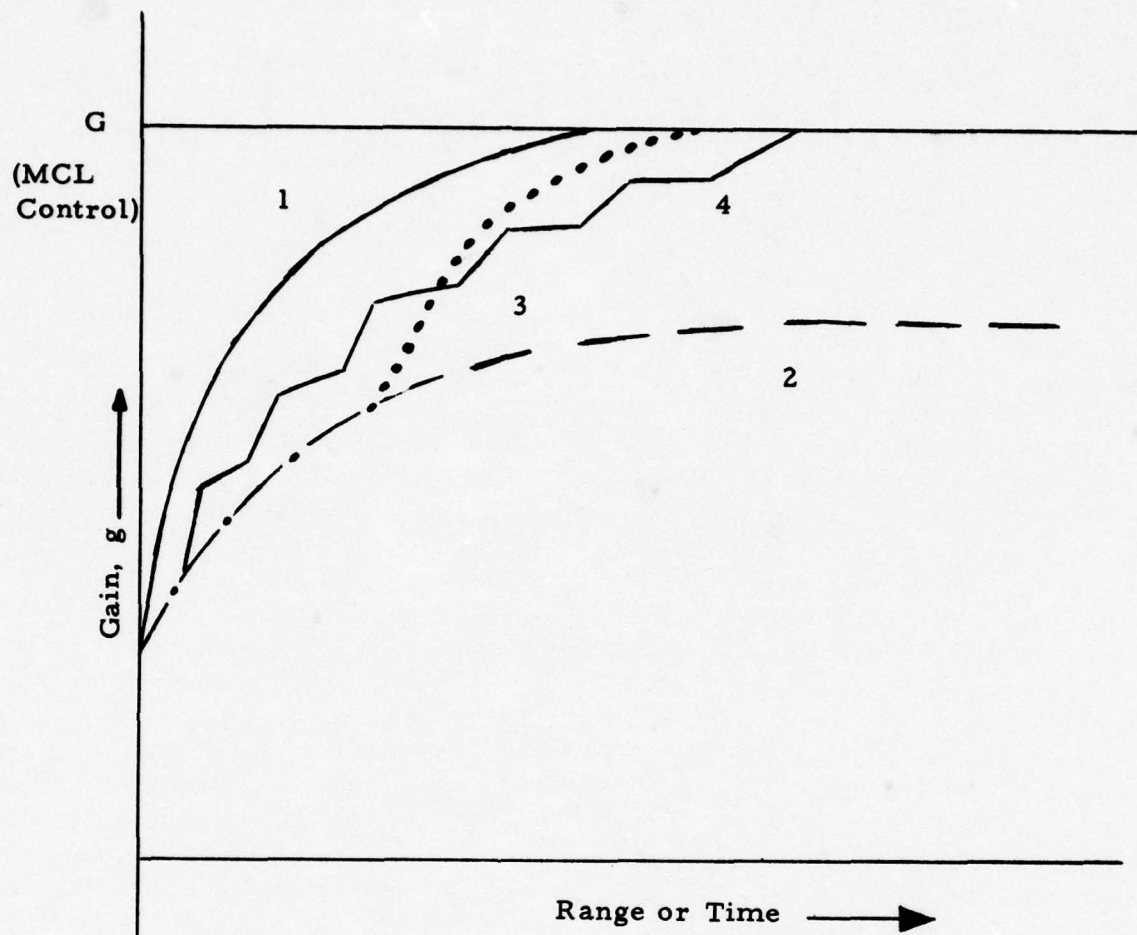


Figure 12. Typical TVG Curves

Our choice of $NR(I)$ can be described in the following relationships:

$$NR(I) = St - 2aR'(I) - 40 \log R'(I) \quad (8)$$

$$NR(I) = 10 \log NR \text{ PR}(I) \quad (9)$$

$NR(I)$ represents the reverberation noise in terms of db while $NR \text{ PR}(I)$ represents reverberation noise as a power ratio. The other terms in (8) and (9) were previously defined.

The second factor to be considered in the overall noise is ship's self noise, NS . The following model is assumed:

$$NS(I) = -38 + 1.65 (Vs - 11) \quad (10)$$

Vs is the ship's speed if it exceeds 11 knots. When the ship's speed is less than 11 knots, Vs is taken to equal 11.

$$NS(I) = 10 \log NSPR(I) \quad (11)$$

$NS(I)$ represents own ship's noise in terms of db while $NSPR(I)$ represents own ship's noise as a power ratio.

The noise level used in our model is based upon the self noise standard for the DD710 class of destroyers ¹². Sources of noise other than due to own ship or reverberation were found to be negligible.

The overall noise factor can be described in the following way:

$$N(I) = 10 \log (NSPR(I) + NRPR(I)) + g \quad (12)$$

Range dependent variations in noise are included in the $R'(I)$ factors. Range independent variations in noise are considered to be incorporate in the term $V(I)$. As will be seen in the next section, the primary interest in variations in noise and signal appear in relations that are dependent on the difference between noise and signal. If we were to include the same $V(I)$ in both noise and signal relations in the difference equations, the variations would cancel out. We could, of course, include separate variation factors, $VN(I)$ and $VE(I)$ in the noise and signal relations and recognize that there was some degree of correlation between them. Then in the difference relation, we would have two correlated random variates. To simplify our model and avoid the need for estimating correlation coefficients for what are estimates

of variation in many complex and interrelated factors, we have elected to combine all of the range independent variations in the single normally varying $V(I)$.

E. Conversion of Signal to Brightness

Detection by the operator in the decision maker model is based on target brightness relative to the surrounding visual "noise" on the scope. To determine the relative brightness we go back to the basic relationship between scope brightness and grid voltage above cutoff.

$$\frac{I_2}{I_1} = \left(\frac{Ed_2}{Ed_1} \right)^k \quad (13)$$

where,

I_2, I_1 = scope brightness at two different grid voltages

Ed_2, Ed_1 = grid voltages (measured above cutoff)

k = the conversion efficiency of the scope

k typically takes on a value of $3/2$ and the above relationship is sometimes referred to as the $3/2$ power law. It applies fairly well to the broad range of intensities above the visibility threshold and below saturation^{13, 14}. To compare the intensity of a spot with noise and an adjacent one with signal and noise superimposed,

$$\frac{I_{s+n}}{I_n} = \left(\frac{E_{bias} + g_r \sqrt{e^2 + n^2} - Eco}{E_{bias} + g_r n - Eco} \right)^k \quad (14)$$

where,

I_{s+n} = intensity of signal superimposed on noise

I_n = the background noise intensity

E_{bias} = the grid bias voltage

e = the signal voltage

n = the noise voltage

E_{co} = the scope's cutoff voltage

g_r = the voltage gain of the receiver, as a ratio, i. e.,
 $g = 20 \log g_r$.

It is assumed that the signal and noise voltages may be combined vectorially by rms addition. For the present we further assume that the scope is biased at cutoff; that is, the intensity knob is set so that the expanding circle is at the threshold of visibility when the MLC is set to zero. For convenience, we will define ΔI as the intensity of the spot, with signal, above the intensity of the surrounding acoustic noise on the scope.

$$\Delta I = I_{s+n} - I_n \quad (15)$$

thus,

$$\frac{\Delta I}{I} + 1 = \left(\frac{\sqrt{e^2 + n^2}}{n} \right)^k = \left(\frac{e^2}{n^2} + 1 \right)^{\frac{k}{2}} \quad (16)$$

Brightness excess, BE, the parameter used in many psychophysical experiments is thus,

$$BE = \log \frac{\Delta I}{I} = \log \left[\left(\frac{e^2}{n^2} + 1 \right)^{\frac{k}{2}} - 1 \right] \quad (17)$$

In terms of db, the signal and noise voltages may be stated as,

$$E = 10 \log e^2, N = 10 \log n^2$$

or,

$$E - N = 10 \log \left(\frac{e^2}{n^2} \right) \quad (18)$$

hence,

$$BE = \log \left[\left(10^{\frac{E-N}{10}} + 1 \right)^{\frac{k}{2}} - 1 \right] \quad (19)$$

F. Conversion of Saturated Signals

The above relations of course apply to the broad range of intensities above threshold and below saturation.

Let s be the signal level for saturation of the scope and

$$S = 10 \log s^2 \quad (20)$$

In the case where the signal plus noise would saturate the scope, i. e.,

$$g_r \sqrt{e^2 + n^2} > s \quad (21)$$

The effective value of $g_r \sqrt{e^2 + n^2}$ is s in (16).

Hence,

$$\frac{\Delta I}{I} + 1 = \left(\frac{s}{g_r n} \right)^k \quad (22)$$

or,

$$BE = \log \frac{\Delta I}{I} = \log \left[\left(\frac{s}{g_r n} \right)^k - 1 \right] \quad (23)$$

It may be shown that:

$$S-N-g = 10 \log \left(\frac{s}{g_r n} \right)^2$$

hence,

$$BE = \log \left[10^{\left(\frac{S-N-g}{2} \right) \frac{k}{2}} - 1 \right]$$

If both I_{s+n} and I_n are above saturation, i. e.,

$$\left\{ g_r n, g_r \sqrt{e^2 + n^2} \right\} > s$$

then $\frac{\Delta I}{I}$ reduces to zero and the brightness excess in db goes to $-\infty$.

G. Near-Threshold Signals

Near-threshold electrical signal and noise may be considered to be converted to brightness with the same transformation as large sub-saturation signals. The difference between near-threshold and large signals is due to the ambient lighting and its effect on the scope face.

Let us consider the case where ambient light "noise" is significant. The way electrical noise, from reverberation say, adds to ambient lighting noise is not a trivial question. Noise which enters the display system via the scope's electron beam of course, results directly in phosphor luminescence. Ambient light, by contrast, results in both reflection and phosphor luminescence. The question might reasonably be asked if the two effective noises should be added linearly, in an rms fashion or in some other manner. A brief experiment was performed which indicated that at high illuminations the interaction is indeed quite complex; however, at low background levels (.1 ft lambert ambient illumination or less) the two types of brightness can be combined by simple addition, i. e.,

$$I_{e+a} = I_a + I_e \quad (24)$$

where,

I_{e+a} = intensity measured with both ambient illumination and scope excitation by electron beam.

I_a = intensity measured with the scope illuminated by ambient light only.

I_e = intensity measured without ambient light, but with the scope excited by the electron beam.

It should be noted that the use of filters over the face of the scope decreases the effective ambient light, so that a .1 ft lambert level would be reduced even further and the above additive relation would still be valid.

To determine brightness excess in the presence of significant ambient lighting we proceed as before:

$$\frac{I_{e+n+a}}{I_{n+a}} = \frac{I_{e+n} + I_a}{I_n + I_a} = \left(\frac{I_{e+n}}{I_n} \right) \frac{I_n + I_a}{I_n + I_a} \quad (25)$$

or,

$$\frac{I_{e+n+a}}{I_{n+a}} = \frac{\left(\frac{g_r \sqrt{e^2 + n^2}}{(g_r n)^k} \right)^k \frac{I_n + I_a}{I_n + I_a}}{I_n + I_a} \quad (26)$$

where,

I_{e+n+a} = intensity of the electrical signal superimposed on electrical noise and ambient lighting noise.

I_{n+a} = intensity of electrical noise and ambient lighting noise.

Let

$$\Delta I_a = I_{e+n+a} - I_{n+a} \quad (27)$$

Thus,

$$\frac{\Delta I_a}{I_{n+a}} + 1 = \frac{\left(\left(\frac{e}{n} \right)^2 + 1 \right)^{\frac{k}{2}} \frac{I_n + I_a}{I_n + I_a}}{I_n + I_a} \quad (28)$$

$$\frac{\Delta I_a}{I_{n+a}} = \frac{\left(\left(\frac{e}{n} \right)^2 + 1 \right)^{\frac{k}{2}} \frac{I_n - I_n}{I_n + I_a}}{1 + \frac{I_a}{I_n}} = \frac{\left(\left(\frac{e}{n} \right)^2 + 1 \right)^{\frac{k}{2}} - 1}{1 + \frac{I_a}{I_n}} \quad (29)$$

Hence, the brightness excess for the case of non-negligible ambient lighting may be stated as:

$$BE = \log \frac{\Delta I_a}{I_{n+a}} = \log \left[\frac{\left(\frac{10^{\frac{E-N}{10}} + 1 \right)^{\frac{k}{2}} - 1}{1 + \frac{I_a}{I_n}} \right] \quad (30)$$

It can readily be seen that this expression for brightness excess reduces to (19) when,

$$I_a \ll I_n \quad (31)$$

The runs made on the model to date have made the assumption stated in (31). However, the extended detection model will consider the significance of low electrical noise levels and the resulting low gain settings.

VI. DECISION MAKER SUBMODEL

A. Alarm Probability

The probability of an alarm is the probability that a sensory event will cause a change in scanning policy, i. e., the probability that a target was glimpsed. The decision-maker model has as its input the visual signal supplied by the physical world model as well as the scanning policy, the fixation time, the glimpse criterion factor and the detection announcement factors, Q_p and Q_t . The visual signal has two primary characteristics which affect detection: location, and brightness excess. The location is important because it determines the portion of the retina which will be stimulated for each fixation. The probability of alarm varies widely with the position of the retina stimulated. Based on a previous detection study ¹, a target which has a 90% probability of causing an alarm if the center of vision is stimulated has only a 20% probability of causing an alarm if the target were displaced 5° from the center of vision. In other words, an operator's chance of detecting a target can be reduced from 90% to 20% if the target is displaced 2.1 inches on a scope located 24 inches from the operator's eye.

B. Brightness Excess

As would be expected, the brightness excess, BE, was also found to be a prime factor in determining probability of alarm. The relations that govern the probability of alarm were empirically determined (1) to be as follows:

$$\text{Prob of alarm} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^Z E - \frac{1}{2} Z^2 dZ \quad (1)$$

where,

$$Z = 8.0 \text{ BE} - 8.0 \log (.021 \text{ ECC} + .125) \quad (2)$$

$$\text{BE} = \log \frac{\Delta I}{I} \quad (3)$$

ECC = angle of eccentricity in degrees

C. Alarm Hypothesis

To see how the visual signal, scanning policy, fixation time, glimpse criterion factor and detection announcement factors (Q_p and Q_t) are related,

it is necessary to start with some of the basic concepts of signal detection theory (SDT)*. "Detection" in SDT is used the way "alarm" is in this report; it does not refer to an announced detection. In a very elementary way, SDT holds that the two events, "no signal present" and "signal present," may be described by two probability distribution functions of some signal characteristic, as noted in Figure 13. Determination of the presence of a signal occurs by virtue of an arbitrary criterion. If the signal characteristic is observed to be below the threshold, the event "no signal present" is deemed to have taken place. Otherwise, the event "signal present" is deemed to have taken place. The probability of correctly discerning the presence of a signal is represented by the area to the right of the threshold and under the "signal present" distribution function.

In the case of the sonar display, the primary characteristic used by an operator to initially ascertain the presence of a possible target is the brightness excess (corrected for eccentricity angle). In our model, it will be recalled that the brightness excess is generally determined by the relation,

$$BE = \log \left[\left(10^{\frac{E-N}{10}} + 1 \right)^{\frac{k}{2}} - 1 \right]$$

Graphically, the relation of two signals (viewed with the same angle of eccentricity) is shown in Figure 14. As before, the probability of designating the presence of either signal is represented by the areas under the appropriate curve and to the right of the criterion line. The stronger signal is seen to have a greater likelihood of being recognized.

Graphically, the relation of a single signal viewed with two angles of eccentricity is shown in Figure 15. The signal viewed with the greater angle of eccentricity is shown to have the smaller probability of being recognized. Up to this point nothing has been said about the shape of the distributions, however, as was previously noted, it was empirically determined that the curves shown in Figures 14 and 15 could be described by the normal probability distribution function (equations (1) through (3)).

D. Glimpse Criterion Factor

For the sonar operator, the criterion may be considered essentially a local constant--local because its level will be different for different areas of the scope, depending on whether the area contains a reef, school of fish or a sector which is the prime responsibility of another ASW ship. The

* For a detailed explanation of SDT see for example references 15 and 16.

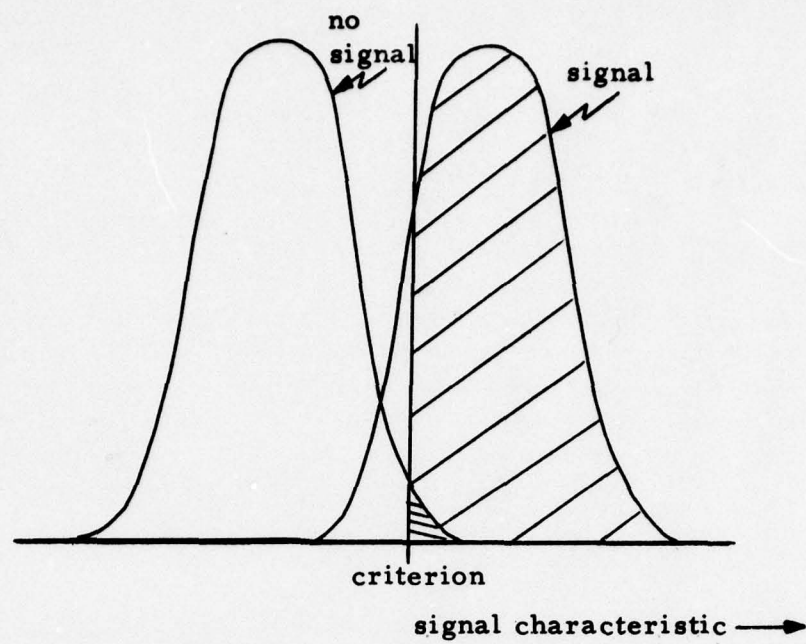


Figure 13. Distribution functions of the events "no signal present" and "signal present."

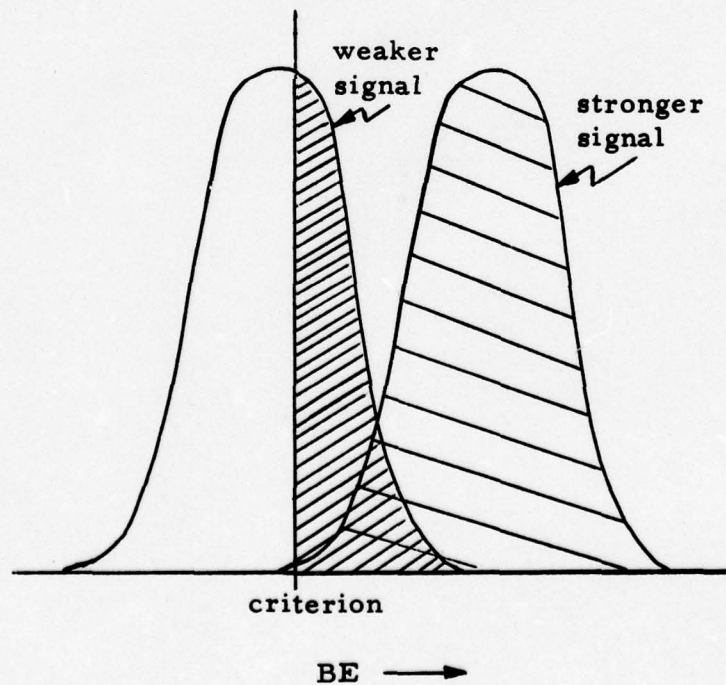


Figure 14. Distribution functions of two signals of different strengths.

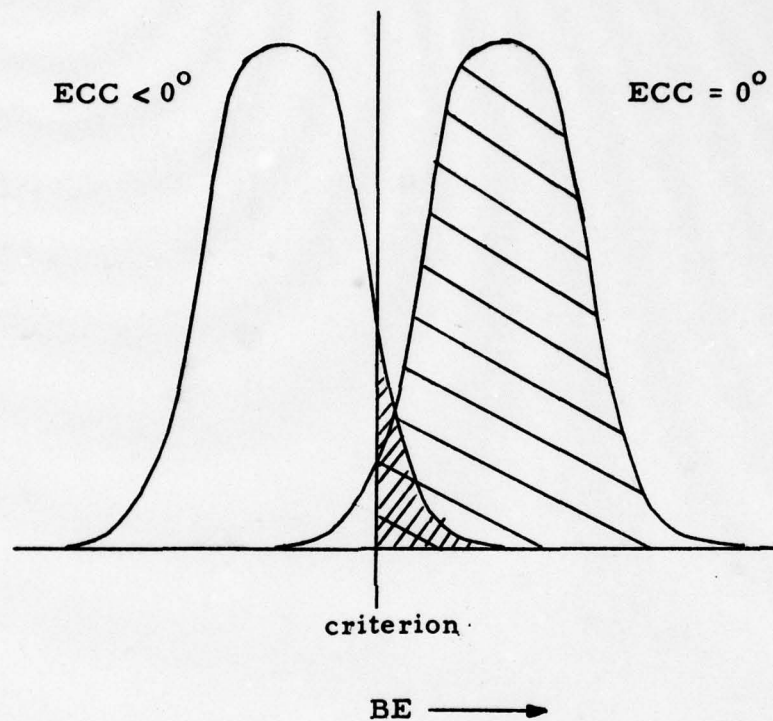


Figure 15. Distribution functions of two signals viewed with two angles of eccentricity.

criterion may be considered relatively constant since the factors that the operator uses to set his criterion level are believed to be relatively constant from ping to ping. These factors include the noise level, the operator's data handling capability and his conservatism (influenced perhaps by comments from the ship's command, "be very sure of any detections reported, or enemy submarines have been reported in this area, report any possible contacts at once"). In the referenced experiment, the criterion used was the lowest possible criterion, or threshold criterion. The threshold criterion represents the case where the operator's data handling capability is taxed minimally (in the experiment one target was presented at a time and there were no spurious targets to consider from the last ping). Furthermore, there was no need for the operator to have a conservative set, as there was no penalty for being wrong.

The model does not attempt to treat the various factors that affect the sonar operator's criterion level. Rather, it simply recognizes that the operator's criterion is displaced to the right of the minimum criterion investigated in the laboratory. The degree to which it is displaced is indicated by the glimpse criterion factor. The glimpse criterion factor is defined as the probability of seeing a threshold signal presented with zero degrees of eccentricity from the center of vision. A threshold signal is at a level that would be recognized 50% of the time by an operator with his criterion at the minimal level.

The magnitude of the glimpse criterion factor used in the model may be set at .0001, .001, .01, .1, or .5. The corresponding criterion displacements are shown in Table III. By exercising the model with different levels of the glimpse criterion factor we are able to investigate the sensitivity of the detection range to this factor. Some of the results of such a sensitivity study are presented in Section VIII.

Table III

Displacements for glimpse criterion factors

<u>Glimpse Criterion Factors</u>	<u>Criterion Displacement</u>
.0001	3.72178
.001	3.09262
.01	2.32765
.1	1.28013
.5	0.00000

E. Scanning Policy

The scanning policy and fixation time affect the probability of alarm by virtue of their effect on the eccentricity angle and the limitations imposed by phosphorescent decay. The fixation time denotes the time of dwell for each fixation. The model assumes that targets may be seen only during the time the eye is at rest, i. e., fixating. The scanning policy locates the sequence of fixation points.

The fixation point is based on the scanning policy, the random ping start time, and the target detection history. A typical scanning policy would be for the operator to fixate successively on the expanding range circle at two o'clock, ten o'clock, and six o'clock. This scanning cycle would be continued until a range is reached at which the model of the operator "anticipates" a target because of prior target history. The fixation angle would be switched from, say, two o'clock to twelve o'clock, where the target is "anticipated."

The target is "anticipated" by the operator to be at the last glimpse position as corrected by a rough estimate of velocity across the face of the scope. Thus, if the target was previously glimpsed on ping (i-j) and (i-k), the anticipated position of the target on the i-th ping is:

$$\hat{X}_i = X_{i-j} + \left(\frac{j}{j-k} \right) (X_{i-j} - X_{i-k}) \quad (4)$$

where X and \hat{X} are the actually glimpsed and anticipated distances respectively along an X axis. If the target was glimpsed only once prior to ping i, X_{i-k} is set equal to X_{i-j} and (4) becomes:

$$\hat{X}_i = X_{i-j} \quad (5)$$

Hence, if the target was sighted only once before the i-th ping, the operator will anticipate the target just where he saw it before.

It should be noted that j and k are limited to Q_t . That is, if the operator was instructed to announce a detection based on the last three pings, he does not anticipate a target location based on what occurred more than three pings ago.

F. Target Eccentricity

For each fixation point the model locates the current position of the target and determines whether the range circle has passed that target recently

enough to still be detectable. If it has, the model calculates the brightness excess of the target based on the factors mentioned in the physical world sub-model described previously. The model then calculates the target eccentricity from the operator's center of vision. By setting Z to zero in equation (2), the brightness excess threshold (50% probability point) may be shown to be as follows:

$$\log \frac{\Delta I}{I} = \log (.021 \text{ ECC} + .125) \quad \text{--for BE threshold} \quad (6)$$

G. Brightness Decay

The model does not assume that the operator will glimpse the target as soon as the range circle passes over the current position. Some time after the range circle passes the target position, the target is still visible because of the gradual decay in the phosphor brightness. According to the phosphor characteristic curves of several manufacturers,* the target brightness t seconds after excitation will decay in accordance with the relation:

$$B(t) = B_0 \exp (-3.21 (t^{.363})) \quad (7)$$

However, the background brightness decays at the same rate, leaving the brightness excess unchanged. Throughout the photopic range of vision, the operator's eye is equally sensitive to the brightness excess, regardless of background brightness.

As the intensity of the target continues to decay below the photopic vision range into the scotopic range, the eye no longer has the same sensitivity to the brightness excess. The eye's sensitivity is complicated by the fact that the decline is markedly different in the fovea and periphery. Peripheral vision falls off very markedly as the brightness declines into the scotopic range; however, foveal vision falls off even more sharply. To avoid the need to examine the rather complex nature of the eye's decline in sensitivity, Dunlap and Associates, Inc., performed its probability-of-detection experiments using a P-7 phosphor scope to duplicate the CRT used in the SQS-23. Test targets were "painted" by an expanding range sweep circle so as to simulate the conditions under which a sonar operator would perform his detection activity. Thus, the probability of detection curves developed by Dunlap and Associates, Inc., and used in the model already contain the effects of brightness decay.

*See, e.g., reference 17.

At present the model considers targets capable of alarming the operator only if they have been illuminated within the last second because of phosphor decay. The extended detection model will have the alarm period determined by the signal brightness when it is first painted on the scope.

H. Announcement of Target Detection

Target detection is understood to be the announcement by the operator of target detection after glimpsing the target the requisite number of pings and seeing it directly in the fovea on at least the last ping. It is felt that regardless of the number of previous glimpses of a bright spot on the scope, the operator would not announce a detection without seeing it in his fovea-- where it could be examined for target-like appearance. Peripheral vision simply is not sufficiently acute for more than brightness discrimination in the detection process.

Throughout the detection process, it is assumed that when the operator glimpses the target in his peripheral vision he will automatically shift his gaze to see it clearly in his fovea, the most sensitive part of the retina. This reflexing action had high survival value to our early ancestors for whom a flash of light was a sign of danger which required immediate attention. The probability of the operator seeing it foveally is described by (1) and (2), with ECC set to zero. The need to define this probability more accurately will be examined before the completion of the extended model.

Except for the last ping before announcement, the logic does not require evaluation of the probabilities of foveal visibility after gaze shift to determine detection. Therefore, the model does not evaluate the probability of foveal visibility except for the last ping. (The model, of course, does keep account of the time spent on all foveal events.)

I. Example of Detection Announcement

Probably the most significant factors that are supplied as inputs to the decision maker model are Q_p and Q_t . These are the number of glimpses which must be made by the operator before detection is announced. For example, $Q_p = 2$ and $Q_t = 3$ would indicate that an operator would announce a detection upon glimpsing the target two times out of the last three pings. In using the word glimpse, we mean that the operator saw a target in his peripheral and/or his foveal vision during a ping. If a sonar operator sees the target in his peripheral or foveal vision on any particular ping, he will interrupt his scan pattern on the next ping to try to see it in his fovea. The operator's scanning pattern, thus, will be different from normal if he has glimpsed a target within the last $Q_t - 1$ pings.

In addition to glimpsing a target Q_p out of Q_t times, the model assumes that the operator must see the potential target directly in his fovea, on the last glimpse, for detection to occur. Table IV which follows indicates a sequence of pings prior to announcing a detection. The table illustrates the case where the operator has been instructed to announce a detection if a target appears in any two out of the last three pings.

Table IV

Typical detection sequence

Number	Peripheral Glimpse	Foveal Glimpse	Glimpses Accrued	Detection
77	Yes	No	1	No
78	No	No	1	No
79	No	No	1	No
80	No	No	0	No
81	Yes	Yes	1	No
82	Yes	No	2	No
83	No	No	2	No
84	Yes	No	2	No
85	Yes	Yes	2	Yes

It will be noted that the "glimpse accrued" column always has the number of peripheral "yes's" out of the last three glimpse numbers and the detection column changes from a "no" to "yes" only when the glimpses accrued is two or more and the foveal detection is "yes." It should be noted that the foveal detection is "no" anytime the peripheral column is "no."

J. Criteria Used in Detection

The model carefully delineates two types of criteria used in detection. A subjective criterion, the glimpse criterion factor, affects the probability that a target will be glimpsed; while the objective criteria, the announcement factors (Q_p and Q_t), directly affect the probability that a target will be announced by the sonar operator. Based on discussions with many ASW personnel, it is believed that both the objective and subjective criteria are operative in determining when a possible detection is announced. In common parlance, both factors affect "detection." Heretofore, studies have tended to dwell on the subjective criteria, while the objective criteria and its underlying mechanism were largely overlooked. This is most unfortunate as the objective criterion is more nearly subject to precise control by ship's command. In the past, a statement "don't announce any sonar contacts unless you are certain of them" would affect both of the sonarman's criteria, but in an approximate and unknown way. Indeed, it is hard to think of any order of that nature which could meaningfully impart "levels of certainty" to the operator. Command is virtually forced to require either that almost none or all possible contacts be reported, with no choice of "gray area" in between.

By contrast, it is expected that the study of the objective detection criterion, and its effect on detection range and probability will permit specification of those "gray areas." A typical command controlling the objective criterion would be as follows: "Announce detection if you see a possible target in seven of the last ten pings." Such an order might also affect the operator's subjective criterion as well. "Seven out of ten pings," in addition to being an announcement criterion, also indicates to the operator that the ship's command is willing to wait for ten pings to be sure that a target is worthy of a report. The operator might subconsciously lower his glimpse criterion because a sonar contact is not as urgent as when he is told, say, to report on a basis of "two out of three pings." As an additional matter, when the operator knows he will have to remember and correlate bright spots over ten pings, he is also likely to set a lower glimpse criterion than when he must correlate over a three ping interval, because of limits on his data handling capacity. It is felt that additional study of the effects of specifying different levels of the objective reporting criteria would be desirable on the extended model.

VII. DETECTION MODEL APPLICATION

A. Purpose

The model was exercised in its present state to guide its further development and to indicate the kinds of results that may be possible with the extended model. Since the model is still in a state of development, the conclusions reached must be considered to be quite tentative.

B. Target Course Distribution

The model in its present state of development assumes that target courses are distributed uniformly in all directions. As a result, the probability distribution of β_0 (bearing when the target first crosses the maximum range circle) is decidedly non-uniform. The highest probability of β_0 occurs when the relative bearing is zero degrees, and falls off as the relative bearing increases in a positive or negative direction. The greater the ratio between the ASW ship's speed and the target's speed, the greater is the probability that β_0 will occur at a relative bearing near zero degrees. However, there is some question of the validity of the basic assumption that the targets' courses would be uniformly distributed. It has been pointed out to us that the target has a sensory range advantage over the ASW ship, and as a result can select his relative course to some degree. In some tactical situations, for example, the target may strive to follow a course counter-parallel to that of the ASW ship. In such a tactical situation the target's relative course would have an expected value of 180° , with some standard deviation around the value. (The standard deviation would be larger for conventional submarines than for nuclear powered ones.) To test the significance of a non-uniform distribution it was decided to make comparative runs. The relative target course was distributed uniformly between $+180^\circ$ and -180° for one set of runs and for the other it was constrained to 180° (i. e., we selected the extreme case of zero variance). It was found that there was a statistically significant difference between the two cases, but the differences were not large enough to practically change any of the tentative conclusions drawn from the model in its present state of development. It is evident, however, that the more refined, extended model should have provision for non-uniform distributions of relative target courses.

To indicate the magnitude of the effect of replacing the uniform distribution of target course with an extreme alternative distribution, a special series of runs was made on the model. The run descriptions are described in Table V. There were 1,000 runs in all; in half of them the targets had uniformly distributed courses and in the other half the relative target course was constrained to 180° . In all other respects the two groups of runs were identical:

Table V
Constant course versus random course runs

Variable	Random Course Run	Constant Course Run
Target course	-180° to +180° (unif. dist.)	180°
Target speed	2 to 8 knots (unif. dist.)	2 to 8 knots (unif. dist.)
ASW ship speed	15 to 30 knots (unif. dist.)	15 to 30 knots (unif. dist.)
Scan policy	2, 6, 10 o'clock cycle	2, 6, 10 o'clock cycle
Fixation time	.33 seconds	.33 seconds
Glimpse criteria	.001	.001
Announcement criteria	3 out of 4	3 out of 4
Range scale setting	40,000 yards	40,000 yards
Source level (i. e., transmitted power)	136 db	136 db
Scope conversion efficiency	1.48	1.48
Standard deviation of range factor	.15	.15
Standard deviation of range-independent factor	2 db	2 db
Ping to ping correlation factor	.5	.5

target speeds, maximum range, scan policies, stochastic decisions, etc., were all the same. Figure 16 shows the detection range histogram for the two groups of runs. The ordinates show the number of ships detected per 100 ships at various ranges. The mean detection ranges were found to be 13,322 yards and 12,104 yards for the random course and fixed course targets, respectively. The two means were examined in ten groups of 100 targets to ascertain the confidence limits that could be placed around each mean. The standard deviation of the two means are 663 and 401 yards. If we set up a null hypothesis that both sets of means are merely different samples from the same population, we could evaluate the difference between the two means using the pooled standard deviation of 548 yards. If we assume the mean is normally distributed, the two means, 12,104 and 13,322 yards are statistically different at a 95 percent probability level (two tail test). Hence, we reject the null hypothesis and assert that the two results are significantly different in the statistical sense. Practically, however, a difference of 1,218 yards out of more than 12,000 would not cause us enough concern to discontinue comparative runs with the present model.

Another difference found between the two groups is in the number of targets detected. Table VI summarizes the number of targets detected in groups of 100 targets. If we were again to set up the null hypothesis that the two conditions represented samples of a single larger population, the difference between the number of targets detected by the two groups would be expected to be zero. If the numbers of detected targets are normally distributed, the average difference, 2.8 targets, is statistically different from zero at the 95 percent probability level. Once again we are encouraged to reject the null hypothesis.

In summary, for the conditions of these runs, targets with 180° relative courses would be more likely to be detected, but detection would typically be at smaller ranges.

C. Histogram Shapes

It is interesting to note that the shapes of the curves shown in Figure 16 are quite similar. The ratio between the standard deviation and means of the detection ranges is about .53. Table VII shows how consistent this ratio is for the ten samples of 100 targets run. Table VIII shows the same ratio for a group of runs with the 20,000 yard range scale setting. The characteristic ratio is approximately .43. Tentatively, it seems that this ratio may be a characteristic of the maximum range scale. If such a characteristic ratio should be validly related to the range scale, it would facilitate describing the various detection range histograms. For a particular set of run conditions only the mean detection range would then be needed to describe the range of which 90, 80, 70 percent, etc., of the targets would be detected.

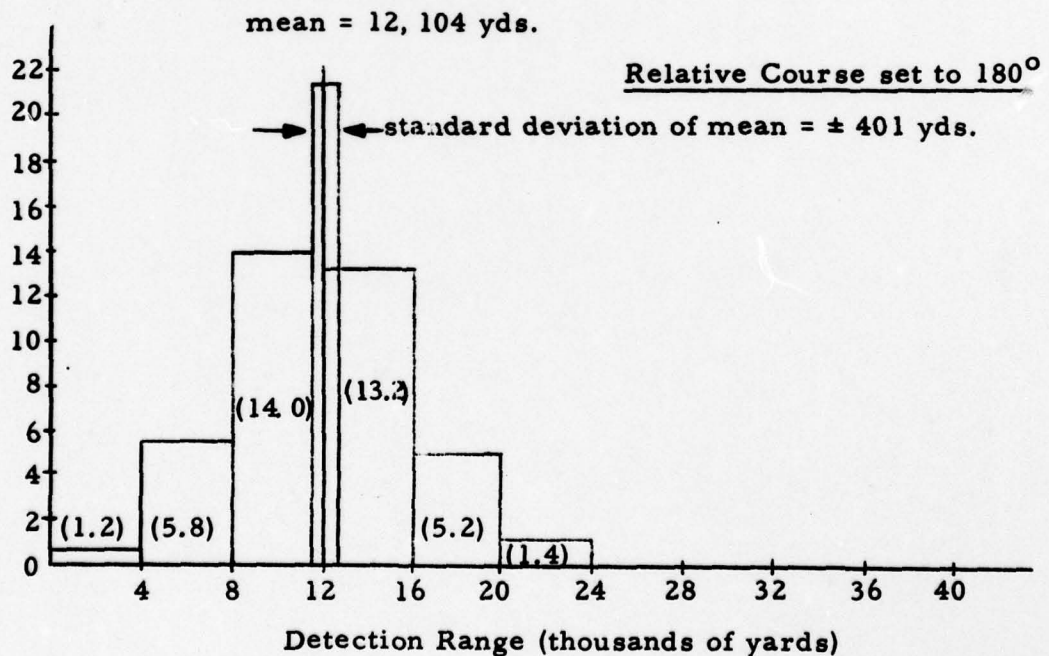
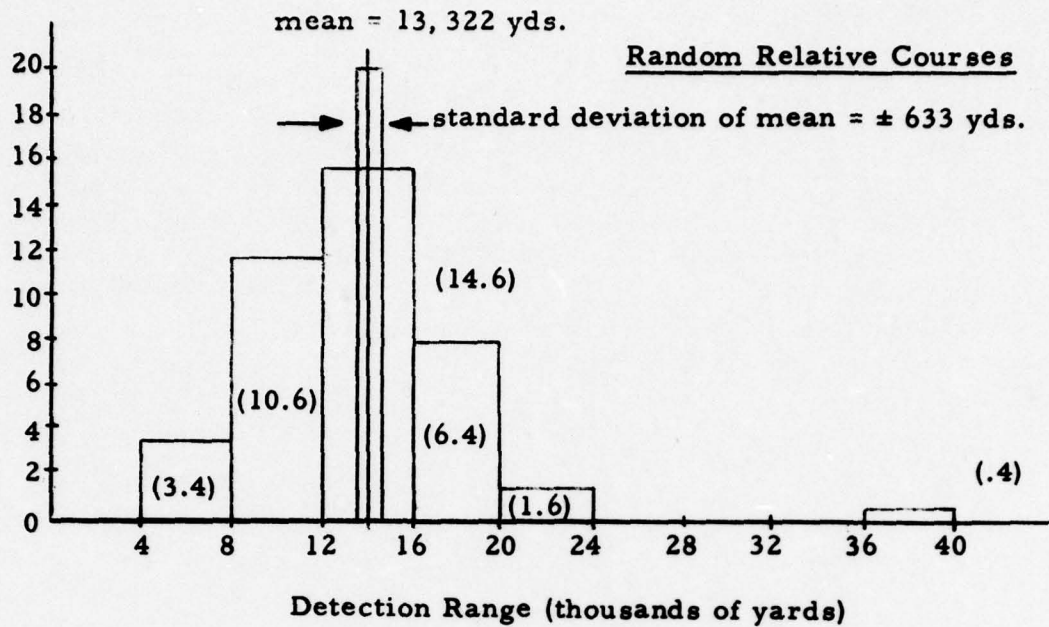


Figure 16. Detection Range Histograms

Table VI
Number of targets detected

	Random Relative Course	180° Relative Course	Difference
Target Group A	36	40	+4
Target Group B	34	37	+3
Target Group C	44	46	+2
Target Group D	38	39	+1
Target Group E	33	37	+4
Average	37.0	39.8	+2.8
Standard Devia- tion of the difference			1.3

Table VII

Standard deviation/mean (40,000 yds.)

	Random Relative		Course	180° Relative Course		
	Mean	Standard Deviation	Ratio	Mean	Standard Deviation	Ratio
Target Group A	12,849 yd.	6,601 yd.	.514	11,815 yd.	6,346 yd.	.537
Target Group B	13,562 yd.	6,905 yd.	.509	12,612 yd.	6,604 yd.	.524
Target Group C	12,549 yd.	6,640 yd.	.529	11,721 yd.	6,272 yd.	.535
Target Group D	14,258 yd.	7,913 yd.	.555	11,919 yd.	6,356 yd.	.533
Target Group E	13,392 yd.	7,124 yd.	.532	12,452 yd.	6,601 yd.	.530
Average			.538			.532

Note: See Table V for the key input parameters.

Table VIII

Standard deviation/mean (20,000 yds)

	Mean	Standard Deviation	Ratio
Target... Group 1	16,068	6,330	.394
Target... Group 2	15,344	6,916	.451
Target... Group 3	15,836	6,774	.428
Target... Group 4	15,443	7,019	.455
Target... Group 5	15,654	6,605	.422
Target... Group 6	15,383	6,925	.450
Average			.433

D. Fixation Time

Additional groups of targets were run under a variety of conditions. Tables IX and X summarize the conditions and results. One of the first areas we sought to investigate concerned fixation time; that is, the time operator fixates at any point before moving on to the next one in the scan pattern. Is the fixation time critical? What is the best time?

Comparing the results of runs 1 and 2, 3 and 4, 5 and 6, and 10 and 11, we can see that the mean detection range is better for .33 seconds than 2.0 seconds. However, the difference is only about 400 yards on the average. This difference does not have much statistical significance if the standard deviation of means (corrected for the change in degrees of freedom) calculated for groups A thru E in Section B is even a very rough estimate for groups 1 through 6.

We may conclude, therefore, that if an operator tires and allows himself to dwell on a spot longer than normal, there would be little effect on the range at which a target might be detected.

It is interesting to note that the better fixation time, .33 seconds is not far from the average fixation time which is used by sonar operators.²

E. Scan Pattern

Several scan patterns were evaluated. In Table IX and X, 1, 2, 3, and 5 on line two designates the number of positions in the scan pattern. Table XI summarizes the "clock position" and distance from the scope center of the various fixations. We compare target groups 1 and 3, 1 and 5, 2 and 4, 2 and 6, and 11 and 12 and find little statistical difference between the detection ranges for different scan patterns. Also, there is little statistical inference we can draw from the fraction of targets detected. Scan pattern 3 seems better than 1 or 5, but we could not come to this conclusion with any reasonable degree of statistical confidence with the present amount of data.

Similarly, scan pattern 2 seems slightly better than 3, but this apparent difference may be due to the vagaries of the target samples selected and the limitation of the present runs to conventional submarines. One might suspect based on Koopman's search theory, that scan pattern 2, which concentrates near zero degrees relative bearing, would not be as good as 3 if the targets included the faster nuclear subs. It will be recalled that targets which move slowly relative to the ASW ship speed, will generally have an initial relative bearing near zero degrees--hence, a scan pattern that emphasizes this bearing on the scope can be expected to be more effective.

Table IX

Sample target run data (20,000 yards range scale)

	Target Group Number					
	1	2	3	4	5	6
Fixation time (sec.)	.33	2.0	.33	2.0	.33	.20
Scan pattern (no. pts.)	3	3	1	1	5	5
Mean det. range (yds.)	16,068	15,344	15,836	15,444	15,654	15,383
Std. dev. det. range (yds.)	6,330	6,916	6,774	7,019	6,605	6,925
Mean time till det. (sec.)	354	412	358	390	401	383
Fraction tgts. detected (percent)	87	80	83	79	84	80
Glimpse prob. criterion	.10	.10	.10	.10	.10	.10
Announcement criteria	3:4	3:4	3:4	3:4	3:4	3:4

Table X

Sample target run data (40,000 yard range scale)

	Target Group Number					
	7	8	9	10	11	12
Fixation time (sec.)	.33	.33	.33	.33	2.0	2.0
Scan pattern (no. pts.)	3	3	3	3	3	2
Mean det. range (yds.)	14,809	16,438	13,962	12,122	11,894	12,432
Std. dev. det. range (yds.)	7,782	8,737	7,480	6,366	6,188	6,537
Mean time till det. (sec.)	974	890	1,062	914	913	952
Fraction tgts. det. (percent)	37	40	39	34	34	35
Glimpse prob. criterion	.001	.10	.10	.0001	.0001	.0001
Announcement criteria	3:4	3:4	7:10	7:10	7:10	7:10

Table XI

Fixation designations

Designation	Meridian Cycle or "clock" position	Distance from center of PPI
1	-----	zero
2	10, 12	on expanding range circle
3	2, 6, 10	on expanding range circle
5	8, 12, 4, 10, 2	on expanding range circle

F. Glimpse Criterion

Comparing target group numbers 7 with 8, and 9 with 10, we can get an indication of the importance of the glimpse criterion. For both pairs the mean detection ranges are statistically different at the 95 percent probability level. The confidence with which we can draw this conclusion from this small sample is rather striking. Subject to confirmation by the extended model, these results suggest that a sonar operator would detect targets at greater ranges if steps are taken to raise his glimpse criterion, (i. e., lower the criterion displacement; see Table III). Possibly the easiest way to raise his glimpse probability level is to reduce any conservative set he may have because of the consequence of being wrong. It is suggested that the sonar operator could be trained to shift his censoring function (due to his reluctance to improperly report a possible submarine) from his internalized glimpse criterion to the external announcement criteria. Such a shift would have the practical advantage of placing the responsibility for setting the reporting level with the ship's command. The sonar operator can then feel free to recognize and report as much as he can, as soon as he can, without inhibition.

G. Announcement Criteria

The effect of changing the announcement criteria is illustrated by target group number 8 and 9 (see Figure X). The two runs were identical except that the announcement criteria was "3 out of 4" for group 8, and "7 out of 10" for group 9. From the data gathered, we cannot conclude that any fewer or more targets would be detected when announcing on the basis of "3 out of 4," but the detection range is significantly greater, at the 95 percent confidence level. It is also noted that the average time to detection is shorter. Thus, the criteria "3 out of 4" will notify the bridge more quickly of any contact. By contrast, "7 out of 10" would give later reports, but more certain ones. So far as we can tell from the data, either set of criteria would report the same number of valid targets. For either set of criteria the sonar operator is freed from the responsibility of deciding how sure he must be in order to report. And, by selection of sets of criteria, the ship's command clearly decides on the alert level deemed best for the circumstances.

VIII. THE EXTENDED DETECTION MODEL

The previous chapters have discussed the major updating which has been completed of the basic detection model developed under an earlier general ASW training contract. This updated model, which is considered well in hand in its present form, applies to only a small proportion of all the situations encountered in practice; namely, isothermal water and non-maneuvering targets. Further, the updated model deals only with the major mode of detection using the video scan. It does not include the small but appreciable increase in detection probability due to parallel operation of the audio channel, nor does it take account of the increased speed of correlation and confirmation inherent in bi-modality audio/video operations.

A. Audio Channel

To simulate the audio channels, the signal excess already computed will be acted upon by a function representing the audio beam sensitivity, taking the cursor bearing and target bearing into account. The resultant will be converted to an audio intensity level. Doppler will be computed for the range rate due to target motion. Functions representing the probability of detection versus audio signal intensity and versus doppler will be either taken from the literature or computed from experimental data in the literature. The audio search plan will be a necessary input to the program.

B. Target Maneuvers

Target maneuvers are currently being inserted into the tracking model. Standard acceleration-deceleration curves, turning rates and radius curves and rate of change of depth curves will be used. Target motion will be computed by integration of a series of linear approximations over very short time increments.

C. Layer Effects in Underwater Sound Propagation

Underwater sound propagation effects of thermal layers in the water can be computed following one of several analytical formulations; the AMOS system which is an empirical system, ray path analysis, or normal mode analysis. There are large, detailed computer programs whose primary purposes are oceanographic research, analysis or prediction. Such degree of refinement is not necessary to the aims and methods of our detection simulation. There are, however, shorter formulations used to account for

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thermal gradient or layer effects on sound propagation in programs devised for more general purposes. One formulation, using the results of the U. S. Naval Underwater Sound Laboratory AMOS studies, ¹⁸ is a particularly good candidate for adoption to our program.

D. Effects of Reverberation and Other Environmental Factors

Reverberation calculations need to be modified to conform to the formulation for surface and volume reverberations by Chapman-Harris¹⁰ and to the formulation for shallow water bottom reverberation by K. V. Mackenzie,¹¹ the most authoritative sources for such calculations. The Chapman-Harris formulation takes wind speed into account. The effects of wind direction and sea state should also be taken into account and be used as controllable parameters. The primary effect of sea state, other than wind effects considered by Chapman-Harris, is the effect on probability of quenching. Relative wind direction is known to affect sound propagation. Authoritative source literature must be found to implement consideration of this effect.

E. Eye Movement Patterns

The present program has the capability of introducing any repetitive eye movement pattern in terms of range circle range and clock position. The program must be slightly modified to accept a semi-random scan pattern developed from the results of our eye movement study.²

F. Target Course, Speed and Bearing Distributions

Our simulation model assumes that target course will vary uniformly from 0° to 360°, that target speed will vary uniformly over the range selected, and that target bearing will be randomly selected from a probability distribution resulting from the additional assumption that targets are uniformly distributed over an infinite planar sea. We know that submariners try to modify such distributions in their favor by the selection of certain tactics while in the vicinity of a convoy. Previous discussions have pointed out that such variations do indeed affect mean detection ranges. Standards should be based on a reasonable representation of the various tactics which will be encountered or on the optimum of such tactics. This can be simulated by appropriate variation of the probability distribution functions for selection of target course, speed and bearing based on typical tactical scenarios.

G. Variation of Selected Equipment Oriented Parameters

The model is currently capable of accepting variations in sonar source level. Variation in display gain control settings can be implemented with considerable programming effort. This would permit investigation of Optimal Gain Settings based on the psychophysical limits of the operator and the results compared with those of Baker. The effects of less than optimum materiel condition of the sonar could be studied if it were possible to reduce receiver sensitivity and directivity index. Reduction of directivity index is a primary effect of inoperative elements in the transducer staves. The amount of programming effort required to implement such capabilities should be evaluated. The effect on tracking accuracy of various levels of range calibration error, bearing alignment error, and error in estimation of the speed of sound in water would all provide useful knowledge. If controllable parameters can be easily introduced to represent each of these errors, it will be done. The first two would be useful in determining required levels of calibration and alignment accuracy, and to evaluate the urgency of recalibration or realignment. The last would be useful in evaluating the frequency of bathythermograph drops and perhaps the need for better means of measuring sound velocity in water. Such information, however, is not required for the establishment of operator search and detection performance standards.

H. Comparison of Simulation Results with Fleet Detection Data

When the model is completed, the results of the simulation should be compared to the results of fleet exercises as contained in the Fadap data base. A good compilation of such data is contained in an article by Cdr. E. W. Sapp¹⁹ which will be used as a basic reference. One problem in the use of such data is that the criterion level in terms of Q_p returns in Q_t pings was not specified, hence reasonable levels would need to be assigned to represent the exercise alerted operator and his probable detection/classification procedures in our simulation. Such comparison would provide some level of preliminary validation of the simulation model. The results of the simulation with appropriate criterion levels could then be used with some degree of confidence to establish operator detection standards.

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